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PHYSICS

WITH APPLICATIONS

BY

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PREFACE

A SPECIAL feature of the present volume is the emphasis given to the practical aspects of physics and to many picturesque phases of the subject. This emphasis has made it possible to introduce numerous interesting commercial applications of the science and to present that side of the subject which makes the schoolboy look forward to the study of physics with keen anticipation. At the same time these applications have been kept subordinate to the main principles of the subject. They nowhere assume such predominance that fundamental principles are submerged.

With these new features, the present book retains the same scientific standards, the same logical presentation, and the same clear-cut statements which characterized the authors' former books. It will give the pupil a firm foundation for future work. The scientific statements are fixed in the student's mind by many simple, practical questions and numerous problems, which are well within the grasp of any pupil who has studied elementary algebra.

Especial attention has been given to the language of the book, which will be found unusually simple and direct. Short sentences, careful explanations, direct definitions, and, above all, an inductive development of each principle, all contribute to the simplicity of presentation.

Pictures have been collected which illustrate every phase of physics. These illustrations have a direct bearing on the text where they stand, and serve not only to interest the pupil and help him to master the principles, but also to impress upon him the universality of physics.

Acknowledgment is due to many teachers whose helpful suggestions have been of great aid to the authors; and to the Westinghouse Electric and Manufacturing Company and the Ridgway Dynamo and Engine Company for photographs of electrical and steam machinery.

H. S. C.
H. N. C.

May, 1917.

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PHYSICS WITH APPLICATIONS

CHAPTER I

INTRODUCTION

I. MATTER AND ENERGY

1. What is Physics? — In beginning the study of any science it is natural to inquire what it is about. A short definition of any science is unsatisfactory, but it may help to set it off from other sciences in a general survey. Thus, to say that botany is all about plants, zoölogy all about animals, and astronomy all about the heavenly bodies, may serve to give a general idea of what these sciences treat, but a thorough study of any one of them is necessary to understand what it is.

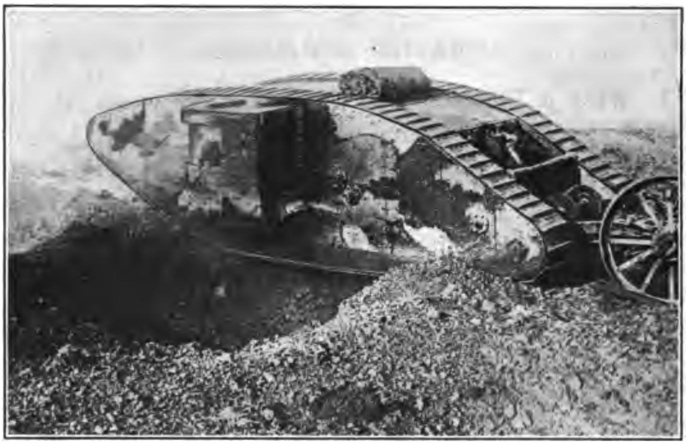
Physics is intimately concerned with *matter* and *energy*. These scarcely admit of definition but only of description by means of their properties. *Matter* is everything we can see, taste, or touch, such as earth, water, wood, iron, gas — in short, everything that occupies space.

Energy is the agency for producing any change in the motion or condition of matter, especially against resistance opposing the change; that is, *energy* may be looked upon as *the universal agency by means of which work is done.* Water in an elevated reservoir, steam under pressure in a boiler, a flying shell with its content of explosives, — all these may do work, may overcome resistance, or change the position or motion of other

bodies. They possess energy which is transferred from them to the bodies on which work is done.

Physics is the science which treats of the related phenomena of matter and energy. It includes the subdivisions: mechanics, sound, light, heat, magnetism, and electricity.

2. Physics a Universal Science. — Since everything we recognize by the senses is matter, and every change in



BRITISH "TANK" CROSSING A SHELL-HOLE.

The tank is a land battleship, carrying guns and running on its own track which it carries with it. In this way it can cross holes and trenches which would stop a vehicle with wheels.

matter involves energy, it is plain that physics is a universal science, touching our life at every point. Countless physical phenomena are taking place about us every day; a girl playing tennis, a boy rowing a boat, the school bell ringing, the sun giving light and heat, a sail flapping in the wind, a bird flying through the air, an apple falling from a tree, a railway train or an automobile

whizzing by, a British "tank" crossing a shell-hole, — all are examples of matter and associated energy.

Physics is not so much concerned with matter alone or with energy alone as with the relations of the two. A baseball is of little interest in itself; it becomes interesting only in connection with a bat and the energy of the player's arm. The engine driver's interest is not so much in the engine itself as in the engine with steam

A MOTOR CAR.

The automobile illustrates some principles in each of the main divisions of physics.

up ready to drive it. No one would care to buy an automobile to stand in a garage; its attractiveness lies in the fact that it becomes a thing of life when its motor is vitalized by the heat of combustion of gasoline vapor.

3. Principles of Physics and their Applications. — The applications of the principles of physics in the household and in the familiar arts are very numerous and affect us constantly in daily life. Water under pressure is deliv-

ered for domestic use, and fuel is used in the liquid or in the gaseous form as well as in the solid. Electricity lights our houses, boils our coffee, toasts our bread, and even cooks our daily food. The electric motor runs our sewing machines and drives our vacuum cleaners. The stable has given place to the garage, which houses a marvel of ingenuity, with its internal combustion engine, its storage battery, its electric generator, electric motor, and electric lights; and the mechanism to utilize all these is of a highly developed type. The mechanics of solids, of liquids, and of gases are all concerned in it; while magnetism, electricity, heat, sound, and light are also illustrated.

The applications of physics in modern life are so numerous and they are changing so rapidly that we cannot expect to learn about all of them in a year's study; but *physical principles* remain the same; and if we acquire a knowledge of these principles and of their familiar applications, we shall be prepared to understand and to explain other applications that have been made possible by the science of physics. So this book lays emphasis on the underlying principles of physics, illustrating them by some of their interesting applications, leaving it to the enthusiasm and ingenuity of both teacher and pupils to supplement the applications with others drawn from life and from scientific and technical journals.

4. States of Matter. — Matter exists in three distinct states, exemplified by water, which may assume either the *solid*, the *liquid*, or the *gaseous* form, as ice, water, or water vapor.

Briefly described,

Solids have definite size and shape, and offer resistance to any change of these.

Liquids have definite size, but they take the shape of the container and have a free surface.

Gases have neither definite size nor shape, both depending on the container.

These are not all the differences between solids, liquids, and gases, but they serve to distinguish between them.

Some substances are neither wholly in the one state nor in the other. Sealing wax softens by heat and passes gradually from the solid to the liquid state. Shoemaker's wax breaks into fragments like a solid under the blow of a hammer, but under long-continued pressure it flows like a liquid, though slowly, and it may be molded at will.

5. Force. — Our primitive idea of force is that of a push or a pull; it is derived from experience in making muscular exertion to move bodies or to stop their motion. Pushing a chair, throwing a stone, pulling a cart, rowing a boat, stretching a rubber band, bending a bow, catching a ball, lifting a book, — all require muscular effort in the nature of a push or a pull. Thus force implies *a push or a pull*, though not necessarily muscular; and the effect of the action of a force on a body free to move is to give it motion or to change

A Trip Hammer.

This weighs several tons and will exert an enormous force on the red-hot iron below it.

its motion. For the present we shall make use of the units of force familiar to us, such as the pound of force and the gram of force, meaning thereby the forces equal to that required to lift the mass of a pound and that of a gram respectively.

II. PROPERTIES OF MATTER

6. **The Properties of Matter** are those qualities that serve to define it, as well as to distinguish one substance from another. All matter has extension or occupies space, and so extension is a *general* property of matter. On the other hand common window glass lets light pass through it, or is transparent, while a piece of sheet iron does not transmit light, or is opaque. A watch spring recovers its shape after bending, or is elastic, while a strip of lead possesses this property in so slight a degree that it is classed as inelastic. So we see that transparency and elasticity are *special* properties of matter.

7. **Extension.** — All bodies have three dimensions, length, breadth, and thickness. A sheet of tissue paper or of gold leaf, at first thought, appears to have but two dimensions, length and breadth; but while its third dimension is relatively small, if its thickness should actually become zero, it would cease to be either a sheet of paper or a piece of gold leaf. *Extension is the property of occupying space or having dimensions.*

8. **Impenetrability.** — While matter occupies space, no two portions of matter can occupy the same space at the same time. The volume or bulk of an irregular solid, such as a lump of coal, may be measured by noting the volume of liquid displaced when the solid is completely immersed in it. *The general property of matter that no two bodies can occupy the same space at the same time is known as impenetrability.*

Put a lump of coal into a tall graduate partly filled with water, as in Fig. 1. Note the reading at the surface of the water before and after putting in the coal; the difference is the volume of water displaced, or the volume of the piece of coal.

FIGURE 1. — MEASURING VOLUME BY DISPLACEMENT.

9. Inertia. — The most conspicuous and characteristic general property of matter is *inertia*. *Inertia is the property which all matter possesses of resisting any attempt to start it if at rest, to stop it if in motion, or to change either the direction or the amount of its motion.* If a moving body stops, its arrest is always owing to something outside of itself; and if a body at rest is set moving, motion must be given to it by some other body. It is a familiar fact that no body of any sort will either start or stop moving of itself.

FIGURE 2. — STATUE TWISTED AROUND BY EARTHQUAKE.

10. Illustrations of Inertia. — Many familiar facts are due to inertia. When a street car stops suddenly, a person standing continues by inertia to move forward, or is apparently thrown toward the front of the car; the driver of a racing motor car is apparently thrown with violence when the rapidly moving car collides with a post or a tree; the fact is the car is violently stopped, while the driver continues to move forward as be-

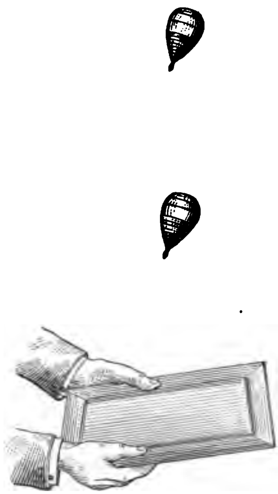


FIGURE 3. — SPINNING TOP MAINTAINS ITS AXIS OF ROTATION.

fore the collision. When a fireman shovels coal into a furnace, he suddenly arrests the motion of the shovel and leaves the coal to move forward by inertia. A smooth cloth may be snatched from under a heavy dish without disturbing it. The violent jar to a water pipe when a faucet is quickly closed is accounted for by the inertia of the stream. Tall columns, chimneys, and monuments are sometimes twisted around by violent earthquake movements (Fig. 2). The sudden circular motion of the earth under a column leaves it standing still, while the slower return motion carries it around. The persistence with which a spinning top maintains its axis of rotation in the same direction is due to its inertia. If it is spun on a smooth surface, like a mirror, and is tossed into the air, it will not tumble over and over, but will keep upright (Fig. 3) and may be caught on the mirror, still spinning on its point. The gyrostat wheel acts on the same principle, and so does Sperry's gyrostatic compass and his stabilizer for ships and aëroplanes.

If a round flat biscuit is pitched into the air, there is no certainty as to how it will come down; but if it is given a spin before it leaves the hand, the axis of spinning keeps parallel to itself (Fig. 4). If one wants to throw a hoop or a hat to some one to catch on a stick, one gives to the hoop or the hat a spin. So also if one wants to throw a quoit and be

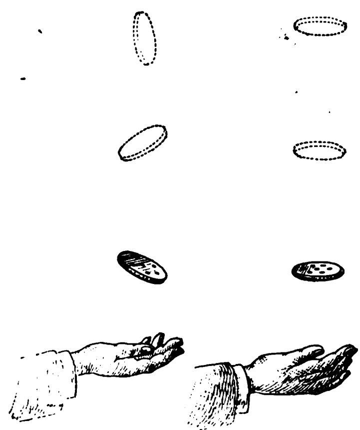


FIGURE 4. — SPINNING BISCUIT.

certain how it will alight, one gives it a spin. Its inertia keeps it spinning around the same axis in space.

Tie a piece of twine to a heavy weight, such as a flatiron. By pulling slowly the flatiron may be lifted, but a sudden jerk on the twine will break it because of the inertia of the weight.

Suspend a heavy weight by a cotton string, as in Fig. 5, and tie a piece of the same string to the under side of the weight. A *steady* downward pull at *B* will break the upper string because it carries the greater load. A *sudden* downward pull on *B* will break the lower string before the pull reaches the upper one on account of the inertia of the weight.

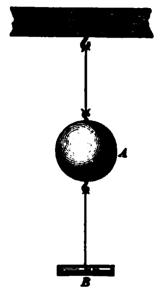


FIGURE 5. — INERTIA EXPERIMENT.

11. Mass. — We are all familiar with the fact that the less matter there is in a body, the more easily it is moved, and the more easily it is stopped when in motion. One can tell an empty barrel from a full one by a kick, a block of wood from a brick by shoving it with the foot, and a tennis ball from a baseball by catching it. The *mass* of a body is the quantity of matter it contains; but since the inertia of a body is proportional to the quantity of matter in it, it is not difficult to see that *the mass of a body is the measure of its inertia.*

While mass is most easily measured by means of weighing, it must not be confused with weight (§ 132), because mass is independent of the earth-pull or gravity. The mass of a meteoric body is the same when flying through space as when it strikes the earth and embeds itself in the ground. If it could reach the center of the earth, its weight would become zero; at the surface of the sun it would weigh nearly twenty-eight times as much as at the earth's surface; but its mass would be the same everywhere. For this reason, and others which will appear later, in discussing the laws of physics we prefer to speak

of *mass* when a student thinks the term *weight* might be used as well.

12. Cohesion and Adhesion. — All bodies are made up of very minute particles, which are separately invisible, and are called *molecules*. *Cohesion is the force of attraction between molecules*, and it binds together the molecules of a substance so as to form a larger mass than a molecule. *Adhesion is the force uniting bodies by their adjacent surfaces.* When two clean surfaces of white-hot wrought iron are brought into close contact by hammering, they *cohere* and become a single body. If a clean glass rod be dipped into water and then withdrawn, a drop will *adhere* to it. Glue, adhesive plaster, and postage stamps stick by adhesion. Mortar adheres to bricks and nickel plating to iron.

WEIGHT AND MASS.

These girders decrease slightly in weight the higher they are lifted from the earth; but their mass is always the same.

Suspend from one of the arms of a beam balance a clean glass disk by means of threads cemented to it (Fig. 6). After counterpoising the disk, place below it a vessel of water, and adjust so that the disk just touches the surface of the water when the beam of the balance is horizontal. Now add weights to the opposite pan until the disk is pulled away from the water. Note that the under surface of the disk is wet. The adhesion of the water to the glass is greater than the cohesion between the molecules of the water. If lycopodium powder be carefully sifted on the surface of the water, the water will not wet the disk and there will be no adhesion. If mercury be substituted for water, a much greater force will be necessary to separate the disk from the mercury, but no mercury will adhere to it. The force of cohesion between the molecules of the mercury is greater than the adhesion between it and the glass.

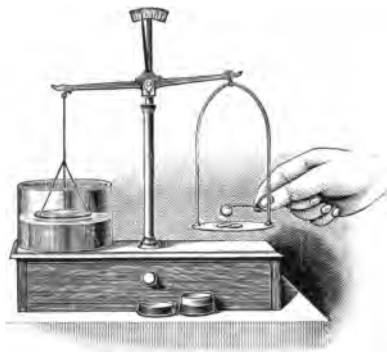


FIGURE 6. — GLASS ADHERES TO WATER.

Cut a fresh, smooth surface on each of two lead bullets and hold these surfaces gently together. They will not stick. Now press them tightly together with a slight twisting motion. They will *adhere* quite firmly. This fact shows that molecular forces act only through insensible distances. It has been shown that they vanish in water at a range of about one five-hundred-thousandth of an inch.

An interesting example of *selective adhesion* occurs in the winning of diamonds in south Africa. The mixed pebbles and other worthless stones, with an occasional diamond, are washed down an inclined shaking surface covered with grease. Only the diamonds and a few other precious stones stick to the grease; the rest are washed away.

13. Porosity. — Sandstone, unglazed pottery, and similar bodies absorb water without change in volume. The water fills the small spaces called *pores*, which are visible either to the naked eye or under a microscope. All matter is

probably porous, though the pores are invisible, and the corresponding property is called *porosity*. In a famous experiment in Florence many years ago, a hollow sphere of heavily gilded silver was filled with water and put under pressure. The water came through the pores of the silver and gold and stood in beads on the surface. Francis Bacon observed a similar phenomenon with a lead sphere.

Oil penetrates into marble and spreads through it. Even so dense a substance as agate is porous, for it is artificially colored by the absorption, first of one liquid and then of another which acts chemically on the first; the result is a deposit of coloring matter in the pores of the agate.

14. Tenacity and Tensile Strength. — *Tenacity is the resistance which a body offers to being torn apart.* The tensile strength of wires is tested by hanging them vertically and loading with successive weights until they break (Fig. 7). The breaking weights for wires of different materials but of the same cross section differ greatly. A knowledge of tensile strength is essential in the design of telegraph wires and cables, suspension bridges, and the tension members of all steel structures.

FIGURE 7. — TENSILE STRENGTH OF WIRE.

Tenacity diminishes with the duration of the pull, so that wires sometimes break with a load which they have supported for a long time. Lead has the least tenacity of all solid metals, and cast steel the greatest. Even the latter is exceeded by fibers of silk and cotton. Single fibers of cotton can support millions of times their own weight.

15. Ductility. — *Ductility is the property of a substance which permits it to be drawn into wires or filaments.* Gold,

copper, silver, and platinum are highly ductile. The last is the most ductile of all. It has been drawn into wire only 0.00003 inch in diameter. A mile of this wire would weigh only 1.25 grains.

MOVABLE BRIDGE FOR CARRYING ORE.

The cables above have great tensile strength for supporting the enormous arms.

Other substances are highly ductile only at high temperatures. Glass has been spun into such fine threads that a mile of it would weigh only one third of a grain. Melted quartz has been drawn into threads not more than 0.00001 inch in diameter. Such threads have nearly as great tenacity as steel.

16. Malleability. — *Malleability is a property which permits of hammering or rolling some metals into thin sheets.*

POURING MOLTEN IRON INTO MOULDS.

Gold leaf, made by hammering between skins, is so thin that it is partially transparent and transmits green light. Zinc is malleable when heated to a temperature of from 100° to 150° C. (centigrade scale). It can then be rolled into sheets. Nickel at red heat can be worked like wrought iron. Malleable iron is made from cast iron by heating it for several days in contact with a substance which removes some of the carbon from the cast iron.

17. Hardness and Brittleness. — *Hardness is the resistance offered by a body to scratching by other bodies.* The relative hardness of two bodies is ascertained by finding which will scratch the other. Diamond is the hardest of all bodies because it scratches all others. Sir William Crookes has shown that diamonds under great hydraulic pressure between mild steel plates completely embed themselves in the metal. Carborundum, an artificial material used for grinding metals, is nearly as hard as diamond.

Brittleness is aptness to break under a blow. It must be

distinguished from hardness. Steel is hard and tough, while glass is hard and brittle.

Tool steel becomes glass-hard and brittle when suddenly cooled from a high temperature. The *tempering* of steel is the process of giving the degree of hardness required for various purposes. It consists usually in first plunging the article at red heat into cold water or other liquid to give it an excess of hardness; then reheating gradually until the hardness is reduced, or "drawn down," to the required degree. The indication of the hardness is the color appearing on a polished portion, such as straw-yellow, brown-yellow, purple, or blue.

The process of *annealing* as applied to iron and glass is used to render them less brittle. It is done by cooling very slowly and uniformly from a high temperature. Soft iron is thus made more ductile, while glass is relieved from the molecular stresses set up in rapid cooling, and it thus becomes tougher and more uniform. The best lamp chimneys are annealed by the manufacturer. Disks of glass for telescope lenses and mirrors must be carefully annealed to prevent fracture and warping during the process of grinding and polishing.

Prince Rupert drops (Fig. 8) are made by dropping melted glass into cold water. The outside is suddenly chilled and solidified, while the interior is still fused, and when it cools it must accommodate itself to the dimensions of the outer skin. The drop is thus under great tension. With a pair of pliers break off the tip of the drop under water in a tumbler, or scratch with a file; the whole drop will fly to powder with almost explosive violence.

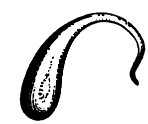


FIGURE 8. — PRINCE RUPERT DROP.

A large tall jar on foot is usually thick at the bottom, and imperfectly annealed. Such jars have not infrequently been broken by a scratch inside, made, for example, by stirring emery powder in water by means of a long wooden stick. A scratch inside is usually fatal to a lamp chimney.

A large glass tube may be cut in two by scratching it around on the *inside* by means of an appropriate tool, and then carefully heating it in a small gas flame.

Exercises

1. Does it disprove the principle of impenetrability to drive a dozen nails into a block of wood without increasing its size? Explain.

2. Why can an athlete jump farther in the running jump than in the standing jump?

3. Why does the jarring of a fruit tree cause the ripened fruit to fall?

4. An ax handle is driven into the ax by pounding the end of the handle rather than the ax. Explain.

5. A man standing on a moving car jumps vertically upward. Does he come down on the spot from which he jumped, or back of it?

6. Why does a bullet shot from a rifle at a window cut a smooth hole through the glass, but if thrown against it by hand shatter it?

7. Could the volume of a crystal of rock candy be determined by the method of § 8?

8. In welding together two pieces of iron, the blacksmith first softens them with heat, cleans the surfaces in contact, and then strikes them with a hammer. Explain.

9. Powdered graphite subjected to great pressure in a suitable mold becomes a hard cake. Explain.

10. It is difficult to drive a nail into a spring board. It is much easier if a heavy hammer is held firmly against the board on the under side. Explain.

11. A rolling wheel does not fall over, but one not rolling must be supported. Explain.

12. Why does a pendulum keep moving when the bob reaches the lowest point of its swing?

13. Imperfect shot are separated from the perfect ones by letting them roll down an inclined plane, across which, near the bottom, is a narrow opening. The defective shot fall into this opening, while the round ones jump over it. Explain.

III. PHYSICAL MEASUREMENTS

18. Units. — To measure any physical quantity a certain definite amount of the same kind of quantity is used as the *unit*. For example, to measure the length of a body, some

arbitrary length, as a foot, is chosen as the unit of length; *the length of a body is the number of times this unit is contained in the longest dimension of the body.* The unit is always expressed in giving the magnitude of any physical quantity; the other part of the expression is the numerical value. For example, 60 *feet*, 500 *pounds*, 45 *seconds*.

In like manner, to measure a surface, the unit, or standard surface, must be given, such as a square foot; and to measure a volume, the unit must be a given volume, such, for example, as a cubic inch, a quart, or a gallon.

19. Systems of Measurement. — Commercial transactions in most civilized countries are carried on by a decimal system of money, in which all the multiples are ten. It has the advantage of great convenience, for all numerical operations in it are the same as those for abstract numbers in the decimal system. The system of weights and measures in use in the British Isles and in the United States is not a decimal system, and is neither rational nor convenient. On the other hand most of the other civilized nations of the world within the last fifty years have adopted the *metric system*, in which the relations are all expressed by some power of *ten*. The metric system is in well-nigh universal use for scientific purposes. It furnishes a common numerical language and greatly reduces the labor of computation.

20. Measures of Length. — In the metric system the unit of length is the *meter*. In the United States it is the distance between two transverse lines on each of two bars of platinum-iridium at the temperature of melting ice. These bars, which are called "national prototypes," were made by an international commission and were selected by lot after two others had been chosen as the "international prototypes" for preservation in the international laboratory on neutral ground at Sevres near Paris. Our national

prototypes are preserved at the Bureau of Standards in Washington. Figure 9 shows the two ends of one of them. The only multiple of the meter in general use is the *kilometer*, equal to 1000 meters. It is used to measure such distances as are expressed in miles in the English system.

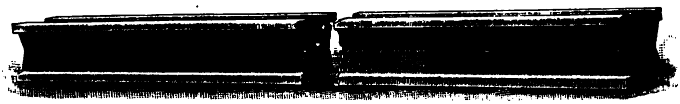


FIGURE 9. — ENDS OF METER BAR.

The Common Units in the Metric System are:

1 kilometer (km.) = 1000 meters (m.)
1 meter = 100 centimeters (cm.)
1 centimeter = 10 millimeters (mm.)

The Common Units in the English System are:

1 mile (mi.) = 5280 feet (ft.)
1 yard (yd.) = 3 feet
1 foot = 12 inches (in.)

By Act of Congress in 1866 the legal value of the yard is $\frac{3600}{3937}$ meter; conversely the meter is equal to 39.37 inches. The inch is, therefore, equal to 2.540 centimeters.

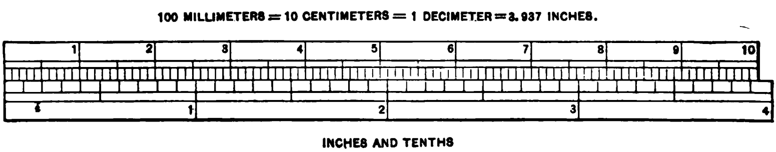


FIGURE 10. — CENTIMETER AND INCH SCALES.

The unit of length in the English system for the United States is the *yard*, defined as above. The relation between the centimeter scale and the inch scale is shown in Fig. 10.

21. Measures of Surface. — In the metric system the unit of area used in the laboratory is the square centimeter (cm.^{3}). It is the area of a square, the edge of which is one centimeter. The square meter (m.^{2}) is often employed as a larger unit of area. In the English system both the square inch and the square foot are in common use. Small areas are measured in square inches, while the area of a floor and that of a house lot are given in square feet; larger land areas are in acres, 640 of which are contained in a square mile.

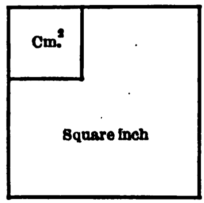


FIGURE 11. — SQUARE CENTIMETER AND SQUARE INCH.

The square inch contains 2.54 × 2.54 = 6.4516 square centimeters. The relative sizes of the two are shown in Fig. 11.

The area of regular geometric figures is obtained by computation from their linear dimensions. Thus the area of a rectangle or of a parallelogram is equal to the product of its base and its altitude ($A = b \times h$); the area of a triangle is half the product of its base and its altitude ($A = \frac{1}{2}b \times h$); the area of a circle is the product of 3.1416 (very nearly $\frac{22}{7}$) and the square of the radius ($A = \pi r^2$); the surface of a sphere is four times the area of a circle through its center ($A = 4\pi r^2$). For other surfaces, see Appendix III.

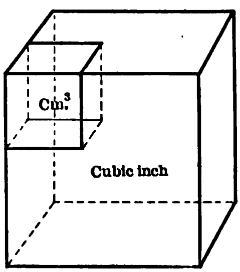


FIGURE 12. — CUBIC CENTIMETER AND CUBIC INCH.

22. Cubic Measure. — The smaller unit of volume in the metric system is the *cubic centimeter*. It is the volume of a cube, the edges of which are one centimeter long. The cubic inch equals $(2.54)^3$ or 16.387 cubic centimeters. The relative sizes of the two units are shown in Fig. 12. In the English system the

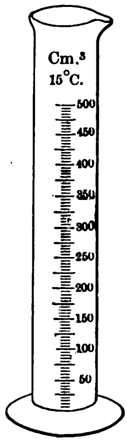


FIGURE 13. — CYLINDRICAL GLASS GRADUATE.

cubic foot and cubic yard are employed for larger volumes. The cubical capacity of a room or of a freight car would be expressed in cubic feet; the volume of building sand and gravel or of earth embankments, cuts, or fills would be in cubic yards.

The unit of capacity for liquids in the metric system is the *liter*. It is a decimeter cube, that is, 1000 cubic centimeters. The imperial gallon of Great Britain contains about 277.3 cubic inches, and holds 10 pounds of water at a temperature of 62° Fahrenheit. The United States gallon has the capacity of 231 cubic inches.

Common Units in the Metric System:

1 cubic meter ($m.^3$)	= 1000 liters (l.)
1 liter	= 1000 cubic centimeters ($cm.^3$)

Common Units in the English System:

1 cubic yard (cu. yd.)	= 27 cubic feet (cu. ft.)
1 cubic foot	= 1728 cubic inches (cu. in.)
1 U. S. gallon (gal.)	= 4 quarts (qt.) = 231 cubic inches
1 quart	= 2 pints (pt.)

The volume of a regular solid, or of a solid geometrical figure, may be calculated from its linear dimensions. Thus, the number of cubic feet in a room or in a rectangular block of marble is found by getting the continued product of its length, its breadth, and its height, all measured in feet. The volume of a cylinder is equal to the product of the area of its base (πr^2) and its height, both measured in the same system of units.

Liquids are measured by means of graduated vessels of metal or of glass. Thus, tin vessels holding a gallon, a quart, or a pint are used

CENTRIFUGAL FORCE. (See page 135.)

Above: Auto Race on a Circular Raised Track.

Below: Sled in Swiss Winter Sports being thrown over the embankment by centrifugal force.

for measuring gasoline, sirup, etc. Bottles for acids usually hold either a gallon or a half gallon, and milk bottles contain a quart, a pint, or a half pint. Glass cylindrical graduates (Fig. 13) and volumetric flasks (Fig. 14) are used by pharmacists, chemists, and physicists to measure liquids. In the metric system these are graduated in cubic centimeters.

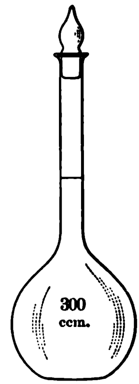


FIGURE 14. — VOLUMETRIC FLASK.

23. Units of Mass. — The unit of mass in the metric system is the *kilogram*. The United States has two prototype kilograms made of platinum-iridium and preserved at the Bureau of Standards in Washington (Fig. 15). The *gram* is one thousandth of the kilogram. The latter was originally designed to represent the mass of a liter of pure water at 4° C. (centigrade scale). For practical purposes this is the kilogram. The gram is therefore equal to the mass of a cubic centimeter of water at the same temperature. The mass of a given body of water can thus be immediately inferred from its volume.

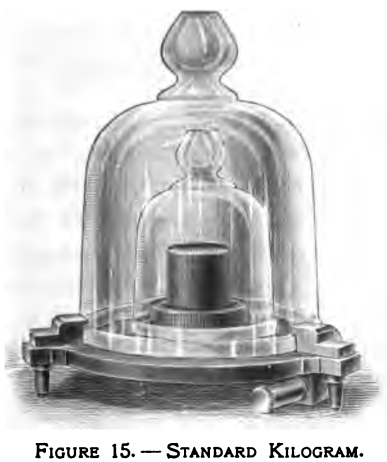


FIGURE 15. — STANDARD KILOGRAM.

The unit of mass in the English system is the *avoirdupois pound*. The *ton* of 2000 pounds is its chief multiple; its submultiples are the *ounce* and the *grain*. The avoirdupois pound is equal to 16 ounces and to 7000 grains.

The "troy pound of the mint" contains 5760 grains. In 1866 the mass of the 5-cent nickel piece was legally fixed at 5 grams; and in 1873 that of the silver half dollar at 12.5 grams. One gram is equal approximately to 15.432 grains. A kilogram is very nearly 2.2 pounds. More exactly, one kilogram equals 2.20462 pounds.

All mail matter transported between the United States and the fifty or more nations signing the International Postal Convention, including Great Britain, is weighed and paid for entirely by metric weight. The single rate upon international letters is applied to the standard weight of 15 grams or fractional part of it. The International Parcels Post limits packages to 5 kilograms; hence the equivalent limit of 11 pounds.

Common Units in the English System:

$$\begin{aligned} 1 \text{ ton (T.)} &= 2000 \text{ pounds (lb.)} \\ 1 \text{ pound} &= 16 \text{ ounces (oz.)} \\ 1 \text{ ounce} &= 437.5 \text{ grains (gr.)} \end{aligned}$$

Common Units in the Metric System:

$$\begin{aligned} 1 \text{ kilogram (kg.)} &= 1000 \text{ grams (g.)} \\ 1 \text{ gram} &= 1000 \text{ milligrams (mg.)} \end{aligned}$$

24. The Unit of Time. — The unit of time in universal use in physics and by the people is the *second*. It is $\frac{1}{86400}$ of a mean solar day. The number of seconds between the instant when the sun's center crosses the meridian of any place and the instant of its next passage over the same meridian is not uniform, chiefly because the motion of the earth in its orbit about the sun varies from day to day. The *mean solar day* is the average length of all the variable solar days throughout the year. It is divided into $24 \times 60 \times 60 = 86{,}400$ seconds of mean solar time, the time recorded by clocks and watches.

The sidereal day used in astronomy is nearly four minutes shorter than the mean solar day.

25. The Three Fundamental Units. — Just as the measurement of areas and of volumes reduces simply to the measurement of length, so it has been found that the measurement of most other physical quantities, such as the speed of a ship, the pressure of water in the mains, the energy consumed by an electric lamp, and the horse power of an engine, may be made in terms of the units of *length*, *mass*, and *time*. For this reason these three are considered *fundamental units* to distinguish them from all others, which are called *derived units*.

The system now in general use in the physical sciences employs the *centimeter* as the unit of length, the *gram* as the unit of mass, and the *second* as the unit of time. It is accordingly known as the *c. g. s.* (centimeter-gram-second) system.

Problems

In solving these problems the student should use the relations and values given in §§ 20 and 22.

1. How many inches in 76 cm.?

2. If a village lot is 4 × 8 rods, how many meters of fence will it take to inclose it?

3. How many kilograms in a ton of coal?

4. How many liters in a gallon?

5. A bushel of wheat weighs 60 lb. How many kilograms in 100 bushels?

6. Calculate the error in the statement that a pint of water weighs a pound.

7. Air under standard pressure weighs 1.293 g. per liter. What is the weight of the air in a room 12 × 30 × 40 ft.?

8. Which is the cheaper, and by how much, milk at 8 cents per quart or at 7 cents per liter?

9. What would be the error made if in measuring 12 ft. the foot rule used was a bar 30 cm. long?

10. Sound has a velocity of 1090 ft. per second. How long does it take sound to travel 1000 m.?

11. A cubic foot of water weighs 62.4 lb. What is the weight of a cubic inch in grains?

12. The greatest allowable weight of a package by foreign parcels post is 5 kg. What is the nearest whole number of pounds?

13. The Washington monument is 555 ft. high. Find its height in meters.

14. A motor boat has a speed of 20 mi. per hour. Express it in kilometers per hour.

CHAPTER II

MOLECULAR PHYSICS

I. MOLECULAR MOTION

26. Diffusion of Gases. — If two gases are placed in free communication with each other and are left undisturbed, they will mix rather rapidly. Even though they differ in density and the heavier gas is at the bottom, the mixing goes on. This process of the spontaneous mixing of gases is called *diffusion.*

The rapidity with which gases diffuse may be illustrated by allowing illuminating gas to escape into a room, or by exposing ammonia in an open dish. The odor quickly reveals the presence of either gas in all parts of the room, even when air currents are suppressed as far as possible. A more agreeable illustration is furnished by a bottle of smelling salts. If it is left open, the perfume soon pervades the whole room.

FIGURE 16. — DIFFUSION OF GASES

Fill one of a pair of jars (Fig. 16) with the fumes of strong hydrochloric acid, and the other with gaseous ammonia, and place over them the glass covers. Bring the jars together as shown, and after a few seconds slip out the cover glasses. In a few minutes both jars will be filled with a white cloud of the chloride of ammonia. Instead of these vapors, air and illuminating gas may be used, and after diffusion, the presence of an explosive mixture in both jars may be shown by applying a flame to the mouth of each separately.

27. Effusion through Porous Walls. — The passage of a gas through the pores of a solid is known as *effusion*. The rate of effusion for different gases is nearly inversely proportional to the square root of their relative densities. Hydrogen, for example, which is one sixteenth as heavy as oxygen, passes through very small openings four times as fast as oxygen.

FIGURE 17. — EFFUSION OF HYDROGEN.

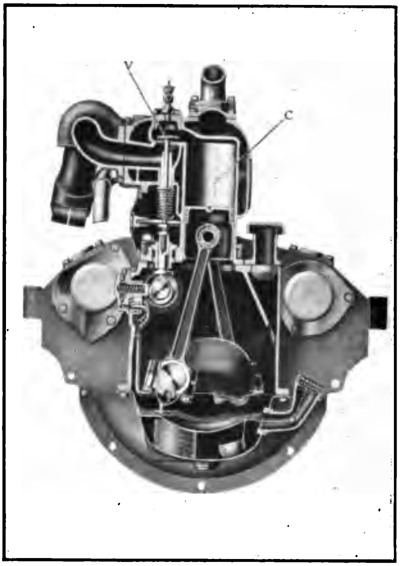
Cement a small unglazed battery cup to a funnel tube, and connect the latter to a flask nearly filled with water and fitted with a jet tube, as shown in Fig. 17. Invert over the porous cup a large glass beaker or bell jar, and pass into it a stream of hydrogen or illuminating gas. If all the joints are air-tight, a small water jet will issue from the fine tube. The hydrogen passes freely through the invisible pores in the walls of the porous cup and produces gas pressure in the flask. If the beaker is now removed, the jet subsides and the pressure in the flask quickly falls to that of the air outside by the passage of hydrogen outward through the pores of the cup.

28. Molecular Motion in Gases. — The simple facts of the diffusion and effusion of gases lead to the conclusion that their molecules (§ 12) are not at rest, but are in constant and rapid motion. The property of indefinite expansibility is a further evidence of molecular motion in gases. No matter how far the exhaustion is carried by an air pump, the gas remaining in a closed vessel expands and fills it. This is not due to repulsion between the molecules, but to their motions. Gases move into a good vacuum much more quickly than they diffuse through one another. In diffusion their motion is frequently arrested by molecular collisions, and hence diffusion is impeded.

The property of rapid expansion into a free space is a

highly important one. The operation of a gasoline engine, in which the inlet valve presents only a narrow opening for a small fraction of a second, is an excellent illustration; and yet this brief period suffices for the explosive mixture to enter and fill the cylinder.

29. Pressure Produced by Molecular Bombardment. — It would be possible to keep an iron plate suspended horizontally in the air by the impact of a great many bullets fired up against its under surface. The clatter of an indefinitely large number of hailstones on a roof forms a continuous sound, and their fall beats down a field of grain flat to the ground. So the rapidly moving molecules of a gas strike innumerable minute blows against the walls of the containing vessel, and these blows compose a continuous pressure. This, in brief, is the kinetic theory of the pressure of a gas.



CROSS SECTION OF AUTOMOBILE MOTOR.

The valve V is open only a fraction of a second, but the gas fills the cylinder C completely.

30. The Velocity of Molecules. — It has been found possible to calculate the velocity which the molecules of air must have under standard conditions to produce by their impact against the walls of a vessel the pressure of one

atmosphere, or 1033 g. per square centimeter. It is about 450 m. per second. For the same pressure of hydrogen, which is only one fourteenth as heavy as air, the velocity has the enormous value of 1850 m. per second. The high speed of the hydrogen molecules accounts for their relatively rapid progress through porous walls.

31. Diffusion of Liquids. — Liquids diffuse into one another in a manner similar to that of gases, but the process is indefinitely slower. Diffusion in liquids, as in gases, shows that the molecules have independent motion because they move more or less freely among one another.

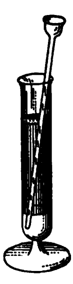


FIGURE 18. — DIFFUSION OF ACID.

Let a tall jar be nearly filled with water colored with blue litmus, and let a little strong sulphuric acid be introduced into the jar at the bottom by means of a thistle tube (Fig. 18). The density of the acid is 1.8 times that of the litmus solution, and the acid therefore remains at the bottom with a well-defined surface of separation, which turns red on the litmus side because acid reddens litmus. But if the jar be left undisturbed for a few hours, the line of separation will lose its sharpness and the red color will move gradually upward, showing that the acid molecules have made their way toward the top.

32. Diffusion of Solids. — The diffusion of solids is much less pronounced than the diffusion of gases and liquids, but it is known to occur. Thus, if gold be overlaid with lead, the presence of gold throughout the lead may in time be detected. Mercury appears to diffuse through lead at ordinary temperatures; in electroplating the deposited metal diffuses slightly into the baser metal; at higher temperatures metals diffuse into one another to a marked degree, so that there is evidence of molecular motion in solids also.

II. SURFACE PHENOMENA

33. Molecular Forces in Liquids. — By an easy transition of ideas we carry the primitive conception of force derived from the sense of muscular exertion over to forces other than those exerted by men and animals, such as those between the molecules of a body. *Molecular forces* act only through insensible distances, such as the distances separating the molecules of solids and liquids. A clean glass rod does not attract water until there is actual contact between the two. If the rod touches the water, the latter clings to the glass, and when the rod is withdrawn, a drop adheres to it. If the drop is large enough, its weight tears it away, and it falls as a little sphere.

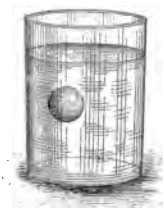


FIGURE 19. — SPHERICAL GLOBULE OF OIL.

By means of a pipette a large globule of olive oil may be introduced below the surface of a mixture of water and alcohol, the mixture having been adjusted to the same density (§ 69) as that of the oil by varying the proportions. The globule then assumes a truly *spherical form* and floats anywhere in the mixture (Fig. 19).

Cover a smooth board with fine dust, such as lycopodium powder or powdered charcoal. If a little water be dropped upon it from a height of about two feet, it will scatter and take the form of little spheres (Fig. 20).

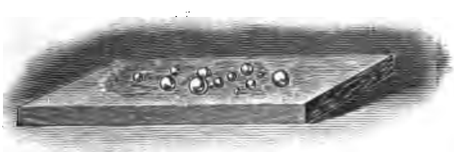


FIGURE 20. — SPHERICAL DROPS OF WATER.

In all these illustrations the spherical form is accounted for by the forces between the molecules of the liquid. They produce uniform molecular pressure and form little spheres, because a spherical surface is the smallest that will inclose the given volume.

34. Condition at the Surface of a Liquid. — Bubbles of gas released in the interior of a cold liquid and rising to the surface often show some difficulty in breaking through. A sewing needle carefully placed on the surface of water floats. The water around the needle is depressed and the needle rests in a little hollow (Fig. 21).

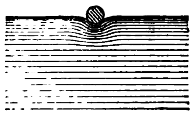


FIGURE 21. — NEEDLE FLOATING ON WATER.

Let two bits of wood float on water a few millimeters apart. If a drop of alcohol is let fall on the water between them, they suddenly fly apart.

A thin film of water may be spread evenly over a chemically clean glass plate; but if the film is touched with a drop of alcohol on a thin glass rod, the film will break, the water retiring and leaving a dry area around the alcohol.

The sewing needle indents the surface of the water as if the surface were a tense membrane or skin, and tough enough to support the needle. This surface skin is weaker in alcohol than in water; hence the bits of wood are pulled apart and the water is withdrawn from the spot weakened with alcohol.

35. Surface Tension. — The molecules composing the surface of a liquid are not under the same conditions of equilibrium as those within the liquid. The latter are attracted equally in all directions by the surrounding molecules, while those at the surface are attracted downward and laterally, but not upward (Fig. 22). The result is an unbalanced molecular force toward the interior of the liquid, so that the surface layer is compressed and tends to contract. The contraction means that the surface acts like a stretched membrane, which molds the liquid into as small a volume as possible. Liquids in small masses, therefore, always tend to become spherical.

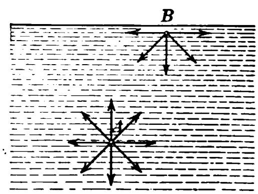


FIGURE 22. — MOLECULAR ATTRACTIONS.

36. Illustrations. — Tears, dewdrops, and drops of rain are spherical because of the tension in the surface film. Surface tension rounds the end of a glass rod or stick of sealing wax when softened in a flame. It breaks up a small stream of molten lead into little sections, and molds them into spheres which cool as they fall and form shot. Small globules of mercury on a clean glass plate are slightly flattened by their weight, but the smaller the globules the more nearly spherical they are.

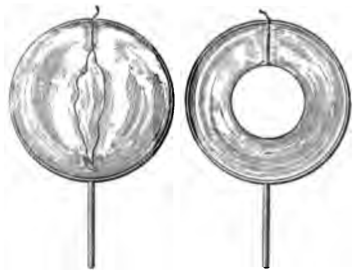


FIGURE 23. — CIRCLE IN LIQUID FILM.

Of stout wire make a ring three or four inches in diameter with a handle (Fig. 23). Tie to it a loop of soft thread so that the loop may hang near the middle of the ring. Dip the ring into a soap solution containing glycerine, and get a plane film. The thread will float in it. Break the film inside the loop with a warm pointed wire, and the loop will spring out into a circle. The tension of the film attached to the thread pulls it out equally in all directions.

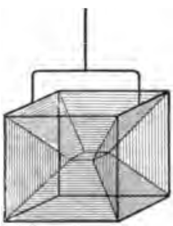


FIGURE 24. — PLANE FILMS.

Interesting surfaces may be obtained by dipping skeleton frames made of stout wire into a soap solution. The films in Fig. 24 are all plane, and the angles where three surfaces meet along a line are necessarily 120° for equilibrium.

A bit of gum camphor on warm water, quite free from an oily film, will spin around in a most erratic manner. The camphor dissolves unequally at different points, and thus produces unequal weakening of the surface tension in different directions.

Make a tiny wooden boat and cut a notch in the stern; in this notch

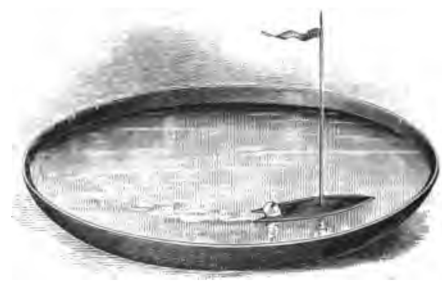


FIGURE 25. — BOAT DRAWN BY SURFACE TENSION.

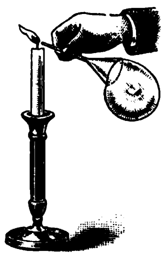


FIGURE 26. — CONTRACTION OF SOAP BUBBLE.

put a piece of camphor gum (Fig. 25). The camphor will weaken the tension astern, while the tension at the bow will draw the boat forward.

Surface tension makes a soap bubble contract. Blow a bubble on a small funnel and hold the open tube near a candle flame (Fig. 26). The expelled air will blow the flame aside, and the smaller the bubble the more energetically will it expel the air.

A small cylinder of fine wire gauze with solid ends, if completely immersed in water and partly filled, may be lifted out horizontally and still hold the water. A film fills the meshes of the gauze and makes the cylinder air-tight; if the film is broken by blowing sharply on it, the water will quickly run out.

37. Capillary Elevation and Depression. — If a fine glass tube, commonly called a capillary or hairlike tube, is partly immersed vertically in water, the water will rise higher in the tube than the level outside; on the other hand, mercury is depressed below the outside level. The top of the little column of water is concave, while that of the column of mercury is convex upward (Fig. 27).

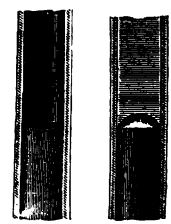


FIGURE 27. — CONCAVE AND CONVEX SURFACES IN TUBES.

Familiar examples of capillary action are numerous. Blotting paper absorbs ink in its fine pores, and oil rises in a wick by capillary action. A sponge absorbs water for the same reason; so also does a lump of sugar. A cotton or a hemp rope absorbs water, increases in diameter, and shortens. A liquid may be carried over the top of a vessel by capillary action in a large loose cord. Many salt solutions construct their own capillary highway up over the top of the open glass vessel in which they stand. They first rise by capillary action along the surface of the glass, then the water evaporates, leaving the salt in fine crystals, through which the solution rises still higher by capillary action. This process may continue until the liquid flows over the top and down the outside of the vessel.

38. Laws of Capillary Action. — Support vertically several clean glass tubes of small internal diameter in a vessel of pure water (Fig. 28). The water will rise in these tubes, highest in the one of smallest diameter, and least in the one of greatest. With mercury in place of water, the depression will be the greatest in the smallest tube.

FIGURE 28. — CAPILLARY ELEVATIONS.

If two chemically clean glass plates, inclined at a very small angle, be supported with their lower edges in water, the height to which the water will rise at different points will be inversely as the distance between the plates, and the water line will be curved as in Fig. 29.

These experiments illustrate the following laws:

FIGURE 29. — CAPILLARY ELEVATION BETWEEN PLATES.

I. *Liquids ascend in tubes when they wet them, that is, when the surface is concave; and they are depressed when they do not wet them, that is, when the surface is convex.*

II. *For tubes of small diameter, the elevation or depression is inversely as the diameter of the tube.*

39. Capillary Action in Soils. — The distribution of moisture in the soil is greatly affected by capillarity. Water spreads through compact porous soil as tea spreads through a lump of loaf sugar. As the moisture evaporates at the surface, more of it rises by capillary action from the supply below. To conserve the moisture in dry weather and in "dry farming," the surface of the soil is loosened by cultivation, so that the interstices are too large for free

capillary action. The moisture then remains at a lower level, where it is needed for the growth of plants.

40. Capillarity Related to Surface Tension. — The attraction of water for glass is greater than the attraction of water for itself (§ 12). When a liquid is thus attracted by a solid, the liquid wets it and rises with a concave surface upward (Fig. 30). The surface tension in a curved film makes the film contract and produces a pressure *toward its center of curvature*, as shown in the case of the soap bubble (§ 36).

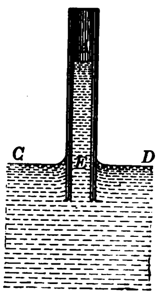


FIGURE 30. — ELEVATION BY SURFACE TENSION.

When the surface of the liquid in the tube is concave, the result of this pressure toward the center of curvature is a force upward; the downward pressure of the liquid under the film is thus reduced, and the liquid rises until the weight of the column AE downward just equals the amount of the upward force. When the liquid is of a sort like mercury, which does not wet the tube, the top of the column is convex, the pressure of the film toward its center of curvature is downward, and the column sinks until the downward pressure is counterbalanced by the upward pressure of the liquid outside.

III. MOLECULAR FORCES IN SOLIDS

41. Solution of Solids. — The solution of certain solids in liquids has become familiar by the use of salt and sugar in liquid foods. The solubility of solids is limited, for it depends on the nature of both the solid and the solvent, — the liquid in which it dissolves. At room temperatures, table salt dissolves about three times as freely in water as in alcohol; while grease, which is practically insoluble in water, dissolves readily in benzine or gasoline.

Solution in a small degree takes place in many unsuspected cases. Thus, certain kinds of glass dissolve to an appreciable extent in hot water. Many rocks are slightly soluble in water; and the familiar adage that the "constant dropping of water wears away a stone" is accounted for, in part at least, by the solution of the stone. Flint glass, out of which cut glass vessels are made, dissolves to some extent in aqua ammonia; this liquid should not be kept in cut glass bottles, nor should cut glass be washed in water containing ammonia.

There is a definite limit to the quantity of a solid which will dissolve at any temperature in a given volume of a liquid. For example, 360 g. of table salt will dissolve in a liter of water at ordinary temperatures; this is equivalent to three quarters of a pound to the quart. When the solution will dissolve no more of the solid, it is said to be *saturated*. As a general rule, though it is not without exceptions, the higher the temperature, the larger the quantity of a solid dissolved by a liquid. A liquid which is saturated at a higher temperature is *supersaturated* when cooled to a lower one.

42. Crystallization. — When a saturated solution evaporates, the liquid only passes off as a vapor; the dissolved substance remains behind as a solid. When the solid thus separates slowly from the liquid and the solution remains undisturbed, the conditions are favorable for the molecules to unite under the influence of their mutual attractions, and they assume regular geometric forms called *crystals*. Similar conditions exist when a saturated solution cools and becomes supersaturated. The presence of a minute crystal of the solid then insures the formation of more. The process of the separation of a solid in the form of crystals is known as *crystallization*.

Dissolve 100 gm. of common alum in a liter of hot water. Hang some strings in the solution and set aside in a quiet place for several hours. The strings will be covered with beautiful transparent octa-

hedral crystals. Copper sulphate may be used in place of the alum; large blue crystals will then collect on the strings.

Filter a saturated solution of common salt and set aside for twenty-four hours. An examination of the surface will reveal groups of crystals floating about. Each one of these, when viewed through a magnifying glass, will be found to be a little cube.

Ice is a compact mass of crystals, and snow consists of crystals formed from the vapor of water. They are of various forms but all hexagonal in outline (Fig. 31).[1]

FIGURE 31. — SNOW CRYSTALS.

43. Elasticity. — Apply pressure to a tennis ball, stretch a rubber band, bend a piece of watch spring, twist a strip of whalebone. In each case the form or the volume has been changed, and the body has been *strained.* A *strain* means either a change in size or a change in shape. As soon as the distorting force, or *stress*, has been withdrawn, these bodies recover their initial shape and dimensions. The word *stress* is applied to the forces acting, while the word *strain* is applied to the effect produced. *The property of recovery from a strain when the stress is removed is called elasticity.* It is called *elasticity of form* when a body recovers its form after distortion; and *elasticity of volume* when the temporary distortion is one of volume. Gases and liquids have perfect elasticity of volume, because

[1] These figures were made from microphotographs taken by Mr. W. A. Bentley, Jericho, Vermont.

they recover their former volume when the original pressure is restored. They have no elasticity of form. Some solids, such as shoemaker's wax, lead, putty, and dough, when long-continued force is applied, yield slowly and never recover.

The elasticity of a body may be called forth by pressure, by stretching, by bending, or by twisting. The bounding ball and the popgun are illustrations of the first; rubber bands are familiar examples of the second; bows and springs of the third; and the stretched spiral spring exemplifies the fourth.

44. Hooke's Law. — Solids have a limit to their distortion, called the *elastic limit*, beyond which they yield and are incapable of recovering their form or volume. The elastic limit of steel is very high; steel breaks before there is much permanent distortion. On the other hand, lead does not recover completely from any distortion.

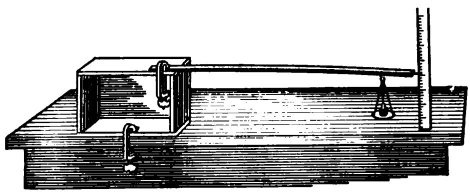


FIGURE 32. — BENDING PROPORTIONAL TO WEIGHT.

When the strain in an elastic body does not exceed the elastic limit, in general *the distortion is proportional to the distorting force*, or *the strain is proportional to the stress*. This relation is known as *Hooke's law.*

Clamp a meter stick to a suitable support (Fig. 32), and load the free end with some convenient weight in a light scale pan; observe the bending of the stick by means of the vertical scale and the pointer. Then double the weight and note the new deflection. It should be double the first. The amount of bending or distortion of the bar is proportional to the weight.

Generally, *for all elastic displacements within the elastic limit, the distortions of any kind, due to bending, stretching, or twisting, are proportional to the forces producing them.*

Questions and Exercises

1. When a glass tube or rod is cut off its edges are sharp. Why do they become rounded by softening in a blowpipe flame?

2. Why does a small vertical stream of water break into drops?

3. Why does a dish with a sharp lip pour better than one without it?

4. A soap bubble is filled with air. Is the air inside denser or rarer than the air outside?

5. Explain the action of gasoline in removing grease spots. How should it be applied so as to avoid the dark ring which often remains after its use?

6. The hairs of a camel's-hair brush separate when placed in water, but gather to a point when the brush is removed from the water. Explain.

7. Are the divisions on the scale of a spring balance equal? What law is illustrated?

8. In the stone quarries of ancient Egypt it is said that large blocks of stone were loosened by drilling a series of holes in the rock, driving in wooden plugs, and then thoroughly wetting them. Explain.

9. Why is it difficult to write on clean glass with a pen?

10. Analysis of the air in a closed room shows little or no difference in its composition in different parts of the room. Explain.

CHAPTER III

MECHANICS OF FLUIDS

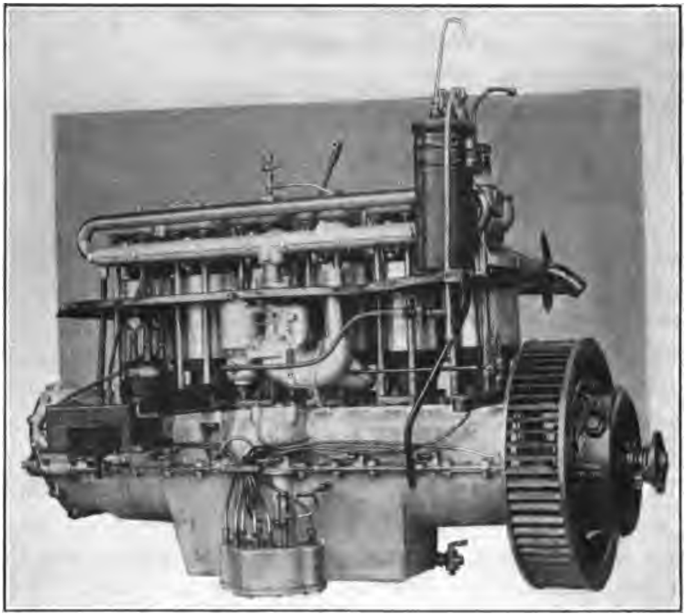
I. PRESSURE OF FLUIDS

45. Characteristics of Fluids. — A fluid has no shape of its own, but takes the shape of the containing vessel. It cannot resist a stress unless it is supported on all sides. The molecules of a fluid at rest are displaced by the slightest force; that is, a fluid yields to the continued application of a force tending to change its shape. But fluids exhibit wide differences in *mobility*, or readiness in yielding to a stress. Alcohol, gasoline, and sulphuric ether are examples of very mobile liquids; glycerine is very much less mobile, and tar still less so.

In fact, liquids shade off gradually into solids. A stick of sealing wax supported at its ends yields continuously to its own weight; in warm weather paraffin candles do not maintain an upright position in a candlestick, but curve over or bend double; a cake of shoemaker's wax on water, with bullets on it and corks under it, yields to both and is traversed by them in opposite directions. At the same time, sealing wax and shoemaker's wax when cold break readily under the blow of a hammer.

46. Viscosity. — *The resistance of a fluid to flowing under stress is called viscosity.* It is due to molecular friction. The slowness with which a fine precipitate, thrown down by chemical action, settles in water is owing to the viscosity of the liquid; and the slow descent of a cloud is

accounted for by the viscosity of the air. Viscosity varies between wide limits. It is less in gases than in liquids; hot water is less viscous than cold water; hence the relative ease with which a hot solution filters.



THE MOBILITY OF GASOLINE VAPOR.

In this six-cylinder automobile engine, gasoline from the tank at the right is vaporized in the carburetor at the center. The mobility of the vapor is so great that it passes readily through the pipe to the cylinders.

47. Liquids and Gases. — Fluids are divided into liquids and gases. *Liquids*, such as water and mercury, are but slightly compressible, while *gases*, such as air and hydrogen, are highly compressible. A *liquid* offers great resistance to forces tending to diminish its volume, while a *gas* offers relatively small resistance. Water is reduced only

0.00005 of its volume by a pressure equal to that of the atmosphere (practically 15 lb. to the square inch), while air is reduced to one half its volume by the same additional pressure. *Pressure means force per unit of surface.* Then, too, *gases* are distinguished from liquids by the fact that any mass of gas when introduced into a closed vessel always completely fills it, whatever its volume. A liquid has a bulk of its own, but a gas has not, since a gas expands indefinitely as the pressure on it decreases.

FIGURE 33. — TRANSMISSION OF PRESSURE.

48. Pressure Transmitted by a Fluid. — Fit a perforated stopper to an ounce bottle, preferably with flat sides, and mounted in a suitable frame (Fig. 33). Fill the bottle with water and then force a metal plunger through the hole in the stopper. If the plunger fits the stopper water-tight, the force applied to the plunger will be transmitted to the water as a bursting force; and the whole force transmitted to the inner surface of the bottle will be as many times greater than the force applied as the area of this surface is greater than that of the end of the plunger.

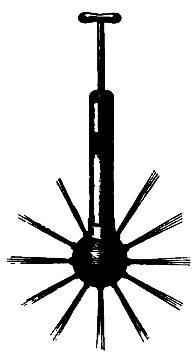


FIGURE 34. — PRESSURE IN ALL DIRECTIONS.

Figure 34 is a form of syringe made of glass; the hollow sphere at the end has several small openings. Fill with water and apply force to the piston. The water will escape in a series of jets of apparently equal velocities, although only one of them is directly in line with the piston.

Fit a glass tube to the stem of a small rubber balloon; blow into the tube; the balloon will expand equally in all directions, forming a sphere and showing equal pressures in all directions. A large soap bubble shows the same thing.

49. Pascal's Principle. — A solid transmits pressure only in the direction in which the force acts; but a fluid trans-

mits pressure in every direction. Hence the law first announced by Pascal in 1653:

Pressure applied to an inclosed fluid is transmitted equally in all directions and without diminution to every part of the fluid and of the interior of the containing vessel.

This is the fundamental law of the mechanics of fluids. It is a direct consequence of their mobility, and it applies to both liquids and gases.

50. The Hydraulic Press. — An important application of Pascal's principle is the *hydraulic press.* Figure 35 is a section showing the principal parts. A heavy piston P works water-tight in the larger cylinder A, while in the smaller one the piston p is moved up and down as a force pump; it pumps water or oil from the reservoir D and forces it through the tube C into the cylinder A. When the piston p of the pump is forced down, the liquid transmits the pressure to the base of the larger piston, on which the force R is as many times the force E applied to p as the area of the large piston is greater than the area of the small one. If the cross-sectional area of the small piston is represented by a, and that of the large one by A, the ratio between the forces acting on the two pistons is

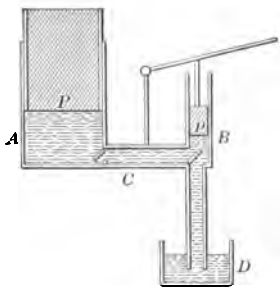


FIGURE 35. — HYDRAULIC PRESS.

$$\frac{R}{E}=\frac{A}{a}=\frac{D^2}{d^2},$$

where D and d are the diameters of the large and small pistons respectively.

Galileo Galilei (1566–1642) was born at Pisa, Italy. He was a man of great genius, and an experimental philosopher of the first rank. He was educated as a physician, but devoted his life to mathematics and physics. He discovered the properties of the pendulum, invented the telescope bearing his name, and was ardent in his support of the doctrine that the earth revolves around the sun. Besides his original work in physics, he made interesting discoveries in astronomy.

Blaise Pascal (1623–1662) was born at Clermont in Auvergne. He was both a mathematician and a physicist. Even as a youth he showed remarkable learning, and at the age of seventeen achieved renown with a treatise on conic sections. He is best known for his announcement in 1653 of the important law of fluid pressure bearing his name. He distinguished himself by his researches in conic sections, in the properties of the cycloid, and the pressure of the atmosphere.

Thus, if the area A is 100 times the area a, a force of 10 pounds on the piston p becomes 1000 pounds on P. The hydraulic press is a device which permits of the exertion of enormous forces.

51. Application of the Hydraulic Press.— This machine is used in the industries for lifting very heavy weights and for compressing materials into small volumes. Instances of the former use are the lifting of large crucibles filled

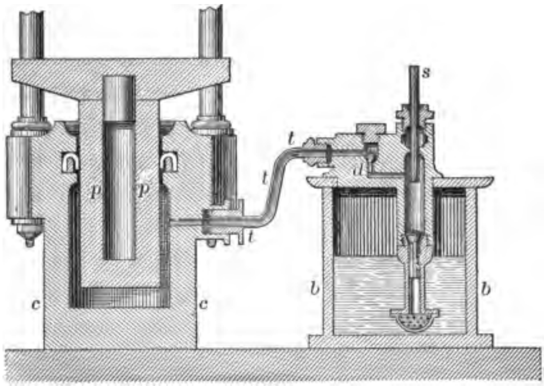


FIGURE 36.— COMMERCIAL HYDRAULIC PRESS.

with molten steel, and of locomotives to replace them on the track. The enormous force of the hydraulic press is applied also to the baling of cotton and paper, to punching holes through steel plates, to making dies, embossing metal, and forcing lead through a die in the manufacture of lead pipe. A small white pine board one inch thick, compressed in an hydraulic press to a thickness of three-eighths inch, becomes capable of a high polish and has many of the properties of hard wood.

The commercial press (Fig. 36) is the same in principle as Fig. 35, with the addition of some auxiliary parts to

make a working machine. The piston s of the force pump may be worked by any convenient power. It has a check valve d which closes when s rises and prevents the return of the water from the large working cylinder. The piston P is surrounded by a peculiar leather collar, without which the press is a failure. The larger the pressure in P, the closer the leather collar presses against the piston and prevents leakage. The upper portion of the machine, cut away in the figure, differs according to the use to which the press is put.

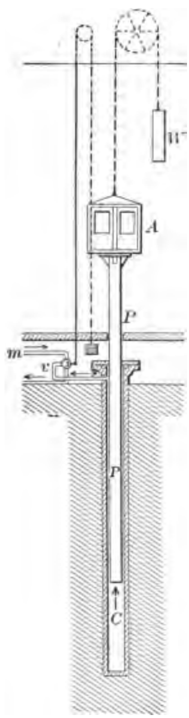


FIGURE 37. — HYDRAULIC ELEVATOR.

If the ratio between the cross-sections of the two pistons is 500, then when s is pressed down with a force of 100 lb. the piston P is forced up with a force of 50,000 lb.

In the hydraulic press it is evident that the small piston travels as many times farther than the large one as the force exerted by the large piston is greater than the effort applied to the small one.

52. The Hydraulic Elevator. — A modern application of Pascal's principle is the hydraulic elevator. A simple form is shown in Fig. 37. A long piston P carries the cage A, which runs up and down between guides and is partly counterbalanced by a weight W. The piston runs in a tube C sunk in a pit to a depth equal to the height to which the cage is designed to rise. Water under pressure enters the pit from the pipe m through the valve v. Turned in one direction the valve admits water to the sunken cylinder,

and the pressure forces the piston up ; when the operator turns it in the other direction by pulling a cord, it allows the water to escape into the sewer, and the elevator descends by its own weight.

When greater speed is required, the cage is connected to the piston indirectly by a system of pulleys. The cage then usually runs four times as fast and four times as far as the piston.

53. Downward Pressure of a Liquid. — Pascal's principle relates to the transmission of pressure applied to a liquid in a closed vessel. But a liquid in an open vessel, such as water in a bucket, produces pressure because it is heavy ; and the pressure of any layer is transmitted to every other layer at a lower level. Since each layer adds its pressure, there must be increasing pressure as the depth increases.

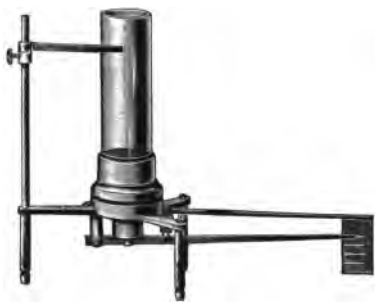


FIGURE 38. — DOWNWARD PRESSURE PROPORTIONAL TO DEPTH.

A glass cylinder is cemented into a metal ferule which screws into a short cylinder, into which fits accurately a plunger. The pointer below, supported by a light spring, acts as a lever, the short arm pressing up against the movable plunger, and the long arm moving in front of a scale (Fig. 38). It should be adjusted to point to zero to begin with. Fill the glass cylinder one third full of water and note the reading of the pointer on the scale. Add water until the cylinder is two thirds full; the reading of the pointer will be doubled. Finally fill the cylinder, and the reading on the scale should be three times the first one. Hence,

The downward pressure is proportional to the depth.

Repeat the experiment with a saturated solution of common salt, which is heavier than water. Every pointer reading will be greater

than the corresponding ones with water, but the same relation will exist between them. Hence,

The downward pressure of a liquid is proportional to its density (§ 69).

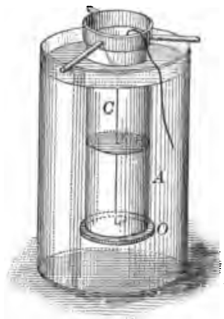


FIGURE 39. — UPWARD PRESSURE.

54. Upward Pressure. — Let a glass cylinder A (Fig. 39), such as a straight lamp chimney, have its bottom edge ground off so as to be closed water tight by a *thin* piece of glass O. Holding this against the bottom of the cylinder by means of a thread C, immerse the cylinder in water. The thread may then be released and the bottom will stay on because the water presses up against it. To release the bottom we shall have to pour water into the cylinder until the levels inside and outside are the same. The upward pressure on the bottom of the cylinder is then the same as the downward pressure inside at the same depth. Or,

In liquids the pressure upward is equal to the pressure downward at any depth.

55. Pressure at a Point. — The three glass tubes of Fig. 40 have short arms of the same length, measured from the bend to the mouth. They open in different directions, — upward, downward, and sidewise. Place mercury to the same depth in all the tubes, and lower them into a tall jar filled with water. When the open ends of the short arms are kept at the same level, the change in the level of the mercury is the same in all of them. Hence,

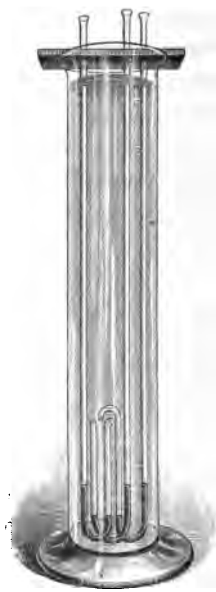


FIGURE 40. — PRESSURE SAME IN ALL DIRECTIONS.

The pressure at a point in a liquid is the same in all directions.

The equality of pressure in all directions may also be inferred from the absence of currents in a vessel of liquid, since an unbalanced pressure would produce motion of the liquid.

FIGURE 41. — PRESSURE INDEPENDENT OF SHAPE.

56. Bottom Pressure Independent of the Shape of the Vessel. — Proceeding as in § 53, use in succession the three vessels shown in Fig. 41. They have equal bases, but differ in shape and volume. They are known as Pascal's vases. Fill each in succession to the same height, and note the reading of the pointer. It will be the same for all, notwithstanding the great difference in the amount of water. Hence,

The downward pressure in a liquid is independent of the shape of the vessel.

The apparent contradiction of unequal masses of a liquid producing equal pressures is known as the *hydrostatic paradox.*

Thus, suppose the circular bottom of a tin pail has an area of 200 cm.^{2} It would be about 16 cm. in diameter. Suppose the pail filled with water to a depth of 25 cm. Then the *pressure* on the bottom would be the weight of a prism of water 1 cm.^{2} in section and 25 cm. high, or 25 g., since a cm.^{3} of water weighs one gram.

The *whole force* on the bottom would be $200 \times 25 = 5000$ g., or 5 kg. If the pail flares, it would contain more than 5000 cm.^{3} of water and would require more than 5 kg. of force to lift it, but the pressure on the bottom would be the same.

57. Total Force on Any Surface. — It will be seen from the example in the last section that the pressure on any area is equal to the product of its depth h below the surface of the liquid and the weight d of a unit volume of the liquid, or $p = hd$. If the depth is in centimeters and

the weight in grams, the pressure p in water is equal to the depth h, since a cubic centimeter of water weighs one gram. The pressure is then in grams per square centimeter. But if h is in feet and d in pounds per cubic foot, then $p = h \times 62.4$ pounds per square foot, since a cubic foot of water weighs 62.4 pounds. To get the pressure in pounds per square inch, divide by 144, because there are 144 square inches in a square foot.

The force on any horizontal area A is then

$$P = A \times h \times d \quad . \quad . \quad \text{(Equation 1)}$$

If the given surface is inclined, then the pressure increases from its value at the highest point submerged to its value at the lowest point. In this case h means the mean depth of the area, or the depth of its center of figure. The total force on any given plane area is always normal, that is, perpendicular to it. Equation 1 still applies.

Examples. To calculate the force on the bottom and sides of a cubical box 30 centimeters on each edge, filled with water, and standing on a horizontal plane:

The area of each face is $30 \times 30 = 900$ cm.^{2} Then the force on the bottom at a depth of 30 cm. is $900 \times 30 = 27{,}000$ g. On the sides the pressure varies from zero to 30 g. per square centimeter. The average pressure is halfway down at a point 15 cm. deep and is 15 g. per square centimeter. Hence the force tending to push out each side is $900 \times 15 = 13{,}500$ g.

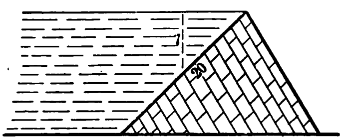


FIGURE 42. — FORCE AGAINST DAM.

The upstream face of a dam measures 20 ft. from top to bottom, but it slopes so that its center of figure is only 7 ft. from the surface of the water when the dam is full (Fig. 42). Find the perpendicular force against the dam for every foot of length.

The area of the face of the dam per foot in length is 20 sq. ft. Hence the weight of the column of water to represent the force is $20 \times 7 \times 62.4 = 8736$ lb.

58. Surface of a Liquid at Rest. — The free surface of a liquid under the influence of gravity alone is horizontal. Even viscous liquids assume a horizontal surface in course of time. The sea, or any other large expanse of water, is a part of the spheroidal surface of the earth. When one looks with a field glass at a long straight stretch of the Suez Canal near Port Said, the water and the retaining wall as contrasting bodies appear distinctly curved as a portion of the rounded surface of the earth.

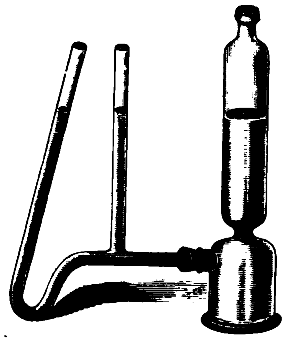


FIGURE 43. — SAME LEVEL IN ALL BRANCHES.

59. Level of Liquid in Connected Vessels. — The water in the apparatus of Fig. 43 rises to the same level in all the branches. (Why should the spout of a teakettle be as high as the lid?) There is equilibrium because the pressures on opposite sides of any cross section of the liquid in the connecting tube are equal, since they are due to liquid columns of the same height.

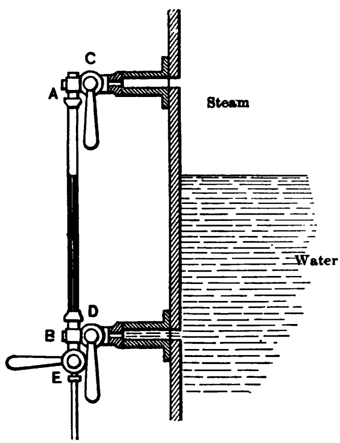


FIGURE 44. — WATER GAUGE.

The glass *water gauge*, used to show the height of the water in a steam boiler, is an important application of this principle. A thick-walled glass tube, AB (Fig. 44), is connected at the top with the steam and at the bottom with the water in the boiler. The pressure of steam is then the same on the water in the boiler and in the gauge tube, and the water level is the same in

the two. The stopcocks C and D are kept open except when it becomes necessary to replace the glass tube. Another stopcock E serves to clean out the tube by running steam through it.

Another application is the *water level*, consisting of two glass tubes, joined by a long rubber tube, and employed by builders for leveling foundations.

60. Artesian Wells. — *Artesian* or *flowing wells* illustrate on a grand scale the tendency of water to "seek its level." In geology an artesian basin is one composed of long strata one above the other. One of these permits the passage of water, and lies between two layers of clay or other material through which water does not pass (Fig. 45).

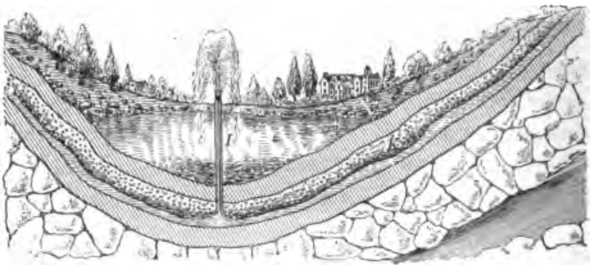


FIGURE 45. — ARTESIAN WELL.

This stratum *K* crops out at some higher level and here the water finds entrance. When a well *I* is bored through the overlying strata in the valley, water issues on account of the pressure transmitted from higher points at a distance. There are 8000 or 10,000 artesian wells in the western part of the United States; some notable ones are at Chicago, St. Louis, New Orleans, Charleston, and Denver. In Europe there are very deep flowing wells in Paris (2360 ft.), Berlin (4194 ft.), and near Leipzig (5740 ft.).

61. City Water Supply. — In some cases, where a supply of water for city purposes is available at an elevation higher than the points of distribution, as in San Francisco, Los Angeles, Denver, and New York, the water from the source, or from a storage reservoir, is conducted to the city in open channels, or in pipes or "mains," and the pressure causing it to flow is due to gravity alone. Arriving at the

ELEPHANT BUTTE DAM.

Largest mass of masonry in the world. The lake formed by the dam is 45 miles long and has a capacity four times that of the Assouan Dam in Egypt, enough to cover the state of Delaware to a depth of two feet.

city, it is distributed through the streets, the pipes terminating at fire hydrants in the streets, and at plugs and faucets in buildings. The water is under pressure adequate to carry it to the highest desired points.

In the absence of a water supply at an elevation, it is necessary to pump the water into a reservoir on a high

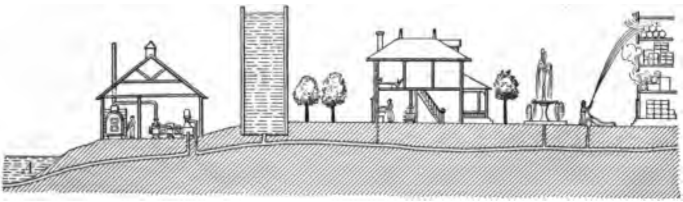


FIGURE 46.—CITY WATER SUPPLY.

point, or into a "standpipe" or water tower as a part of the distributing system. The water rises in the water tower to a height corresponding to the pressure maintained by the pump. This device serves to equalize the pressure throughout the system, and in the smaller systems it may take the place of a reservoir; it may exert pressure for domestic purposes and for fire protection even when the pump is not running (Fig. 46).

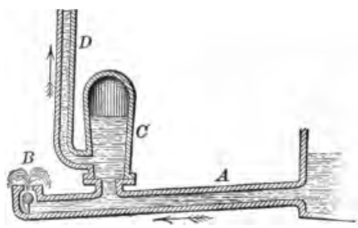


FIGURE 47.—HYDRAULIC RAM.

For limited domestic supply the *hydraulic ram* (Fig. 47) is sometimes used. Its action depends on the inertia of a stream of water in a pipe. The valve at B is normally open and the other valve opening upward into the air dome is closed. The flow of water through the pipe A closes the ball valve B, and the shock of the sudden arrest of the flow opens the valve into the air dome; the water enters to relieve the sudden pressure. Valve B then opens again and the other one closes. The flow thus takes place by a succession of pulses.

Questions and Problems

1. Why do gas bubbles rising through water from a marshy bottom grow larger as they ascend?

2. Why is the water pressure greater in the basement of a house than on the top floor?

3. A force of 150 lb. is applied to a small piston of an hydraulic press; the two pistons have diameters of 1 in. and 5 in. respectively; what force is exerted on the larger one?

4. A swimming tank 50 ft. square is filled with water to a depth of 10 ft. What is the total force on the bottom? On one side?

5. A glass cylinder 76 cm. high is level full of mercury. What is the pressure in grams per square centimeter on the bottom? (1 $cm.^3$ of mercury weighs 13.6 g.)

6. A recording pressure gauge registered zero at the surface of a fresh-water lake and 150 lb. per square inch at the bottom. Calculate the depth of the lake.

7. How high would water rise in the pipes of a building if a pressure gauge shows that the pressure at the ground floor is 40 lb. per sq. inch?

8. If an open bottle full of air is forced into a vessel of water, mouth downward, will any water enter the bottle? Explain.

9. In a city supplied with water from a reservoir, to what height will the water rise in a pipe?

10. Is the pressure against a dam that backs up the water a mile any greater than on one that backs up water half a mile, the depth of water at the dams being the same?

11. What pressure per square inch must be applied in a water supply system to carry water in a pipe to the top of a building 200 ft. high?

12. A cylindrical water tank is 10 ft. in diameter and 10 ft. high. What is the *pressure* on the bottom when the tank is full of water?

13. A water elevator carries an unbalanced weight of 3000 lb. If the piston supporting the elevator is 8 in. in diameter, what pressure of water per square inch is necessary?

14. A vertical tube is filled with mercury, weighing 13.6 g. per cubic centimeter, to a depth of 3 m. What is the pressure in grams per square centimeter on the bottom?

15. What is the pressure per square foot at a depth of 2 mi. in the ocean, sea water weighing 64 lb. per cubic foot?

II. BODIES IMMERSED IN LIQUIDS

62. Buoyancy. — A marble sinks in water and floats in mercury; a fresh egg sinks in water and floats in a saturated solution of common salt; a piece of oak floats in water and the dense wood lignum-vitae sinks; a swimmer in the sea is nearly lifted off his feet by the heavy salt water.

Suspend a pound or two of iron from the hook of a draw scale, and note its weight. Now bring a beaker of water up under the iron and partly immerse it; note that its weight is diminished; immerse farther and the loss of weight increases; after it is fully submerged, the loss of weight does not increase with the depth of immersion. If salt water is used, the apparent loss of weight will be greater; if kerosene, it will be less. In popular language the body immersed is said to have lost weight. Its real weight has not changed in the least; but an upward force has been brought to bear on it.

The lifting force of a liquid on a body immersed in it is called *buoyancy*.

63. The Measure of Buoyancy. — The law of buoyancy was discovered by a Greek philosopher Archimedes about 240 B.C. while engaged in determining the composition of the golden crown of Hiero, king of Syracuse, who suspected that the goldsmith had mixed silver with the gold. The law is as follows:

A body immersed in a liquid is buoyed up by a force equal to the weight of the liquid displaced by it.

The following experiments illustrate the principle of Archimedes, which is the basis of the theory of floating bodies:

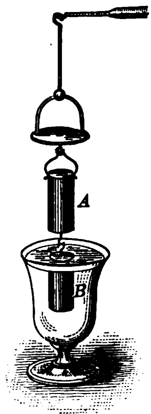


FIGURE 48. — ILLUSTRATING PRINCIPLE OF ARCHIMEDES.

The hollow brass cylinder A (Fig. 48) and the solid brass cylinder B, which exactly fits into A, are suspended from one arm of a balance and carefully counterpoised. If now the cylinder A be filled with water, the equilibrium will be disturbed; but if at the same time cylinder B is immersed in water, as in the figure, the equilibrium will be restored. The upward force on the solid cylinder is therefore equal to the weight of the water in A, and this is equal in volume to that of the immersed cylinder. If the experiment is tried with any other liquid which does not attack brass, the result will be the same.

A metal cylinder 5.1 cm. long, and 2.5 cm. in diameter has a volume of almost exactly 25 cm.^{3} Suspend it by a fine thread from one arm of a balance (Fig. 49) and counterpoise. Then submerge it in water as in the figure. The equilibrium will be restored by placing 25 g. in the pan above the cylinder. The cylinder displaces 25 cm.^{3} of water weighing 25 g., and its apparent loss of weight is 25 g. The temperature of the water should be near freezing.

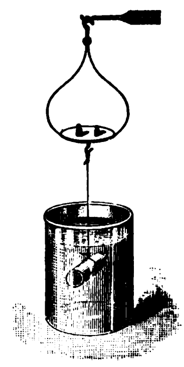


FIGURE 49. — APPARENT LOSS OF WEIGHT.

64. Explanation of Archimedes' Principle. — If a cube be immersed in water (Fig. 50), the pressures on the vertical sides a and b are equal and in opposite directions. The same is true of the other pair of vertical faces. There is therefore no resultant horizontal force. On d there is a downward force equal to the weight of the column of water having the face d as a base, and the height dn. On c there is an upward force equal to the weight of a column of water whose base is the area of c, and whose height is cn.

The upward force therefore exceeds the downward force by the weight of the prism of water whose base is the face *c* of the cube, and whose height is the difference between *cn* and *dn*, or *cd*. This is the weight of the liquid displaced by the cube.

FIGURE 50. — EXPLANATION OF PRINCIPLE.

In general if a cube of any material be immersed in water, the water pressure at every point will be independent of the substance of the cube. Suppose then it is a cube of the water itself. Its weight will be a vertical force downward. But it is in equilibrium, for it does not move. Hence its own weight downward is offset by an equal force acting vertically upward. But this upward force of the water is the same, whatever the material of the cube. Hence, there is an upward force on any submerged cube equal to the weight of the water displaced by it. A similar argument applies to a body of any shape submerged in any liquid.

65. Floating Bodies. — If a body be immersed in a liquid, it may displace a weight of the liquid *less* than, *equal* to, or *greater* than its own weight. In the first case, the upward force is less than the weight of the body, and the body sinks. In the second case, the upward force is equal to the weight of the body, and the body is in equilibrium. In the third case, the upward force exceeds the weight of the body, and the body rises until enough of it is out of the liquid so that these forces become equal. The buoyancy is independent of the depth so long as the body is wholly immersed, but it decreases

as soon as the body begins to emerge from the liquid. Hence,

When a body floats on a liquid it sinks to such a depth that the weight of the liquid displaced equals its own weight.

66. Experimental Proof. — Make a wooden bar 20 cm. long and 1 cm. square (Fig. 51). Drill a hole in one end and fill with enough shot to give the bar a vertical position when floating with nearly its whole length in water. Graduate the bar in millimeters along one edge, beginning at the weighted end, and coat with hot paraffin. Weigh the bar and float it in water, noting the volume in cubic centimeters immersed. This volume is equal to the volume of water displaced; and since 1 $cm.^3$ of water weighs 1 g., the weight of the water displaced is numerically equal to the volume of the bar immersed. This will be found also very nearly, if not quite, equal to the weight of the loaded bar.

FIGURE 51. — EXPERIMENTAL PROOF.

67. The Cartesian Diver. — Descartes, a French scientist, illustrated the principle of flotation by means of an hydrostatic toy, since called the *Cartesian diver*. It is made of glass, is hollow, and has a small opening near the bottom. The figure is partly filled with water so that it just floats in a jar of water (Fig. 52). Pressure applied to the sheet rubber tied over the top of the jar is transmitted to the water, more water enters the floating figure, and the air is compressed. The figure then displaces less water and sinks. When the pressure is relieved, the air in the diver expands and forces water out again. The actual displacement of water is then increased, and the figure rises to the surface. The water in the diver may be so nicely adjusted that the little figure will sink in cold water, but will rise again when the water has reached the tempera-

FIGURE 52. — CARTESIAN DIVER.

ture of the room, and the air in the figure has expanded.

A good substitute for the diver is a small inverted homeopathic vial in a flat 16-oz. prescription bottle, filled with water and closed with a rubber stopper. When pressed, the sides yield, and the vial sinks.

A submarine boat is a modern Cartesian diver on a large scale. It is provided with tight compartments, into which water may be admitted to make it sink. It may be made to rise to the surface by expelling some of the water by powerful pumps.

FIGURE 53. — U. S. SUBMARINE G-2.

68. The Floating Dry Dock. — The floating dock resembles the submarine in principle. It is made buoyant

THE MERCHANT SUBMARINE DEUTSCHLAND.

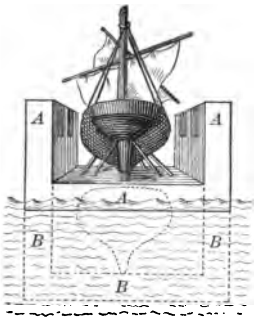


FIGURE 54. — DRY DOCK.

by pumping water out of water-tight compartments, and by floating it lifts a vessel out of the water. In Fig. 54 *A*, *A* are compartments full of air. When they are filled with water, the dock sinks to the dotted position *B*, *B* and the vessel is floated into it. When the water is pumped out, the dock takes the position indicated by the full lines and the vessel is lifted out of water.

III. DENSITY AND SPECIFIC GRAVITY

69. Density. — We are familiar with the fact that bodies of different kinds may have the same size or bulk and yet differ greatly in weight, that is, in mass. A block of steel, for example, is nearly forty times as heavy as a block of cork of the same dimensions, that is, its mass is nearly forty times as great. This difference is expressed as a difference in *density*. *The density of a substance is the number of units of mass of it contained in a unit of volume.*

In the *c.g.s.* system density is the number of grams per cubic centimeter. For example, the density of steel is 7.816 grams per cubic centimeter (expressed as 7.816 g./cm.^{3}), while that of cork has a mean value of about 0.2 g./cm.^{3}, and that of mercury 13.596 g./cm.^{3} So

$$density = \frac{mass}{volume},$$

or in symbols,

$$d = \frac{m}{v}; \text{ whence } m = dv, \text{ and } v = \frac{m}{d}. \qquad \text{(Equation 2)}$$

To illustrate, a slab of marble 20 × 50 × 2 cm. has a volume of 2000 cm.^{3} and weighs 5.4 kg. or 5400 g. Hence its density is 5400/2000 = 2.7 g./cm.^{3}

70. Specific Gravity. — *The specific gravity of a body is the ratio of its weight to the weight of an equal volume of water.* If, for example, a cubic inch of lead weighs 11.36 times as much as a cubic inch of water, the specific gravity of lead is 11.36. The principle of Archimedes furnishes a simple method of finding specific gravity, since the loss of weight of a heavy body suspended in water is equal to the weight of the water displaced, or the weight of a volume of water equal to that of the suspended body. Hence

$$\textit{specific gravity} = \frac{\textit{weight of body}}{\textit{loss of weight in water}}.$$

For example, a piece of copper weighs 880 g. in air and 780 in water. Its loss of weight is then 100 g., and this is the weight of the water displaced. Hence the specific gravity of copper is $880/100 = 8.8$.

71. Density and Specific Gravity Compared. — Specific gravity and density have not quite the same meaning. For example, the specific gravity of lead is the *abstract* number 11.36, while the density of lead is 11.36 g./cm.^{3}, or $62.4 \times 11.36 = 708.9$ lb./cu. ft., both of them *concrete* numbers.

Specific gravity is only a ratio between two masses or weights, and is therefore independent of the units employed in determining it; while density depends on the units used to express it.

In the *c.g.s.* system density and specific gravity are numerically the same, because the density of water is one gram per cubic centimeter, or

$$\textit{density } (g./cm.^3) = \textit{specific gravity}.$$

But in the English system

$$\textit{density } (lb./cu.\ ft.) = 62.4 \times \textit{specific gravity}.$$

It is worth remembering that if the density of any substance is expressed in *c. g. s.* units, its numerical value is always that of the specific gravity. Table IV in the Appendix of this book gives the densities in grams per cubic centimeter.

72. Density of Solids. — The density of a solid body is its mass divided by its volume. Its mass may always be obtained by weighing, but the volume of an irregular solid cannot be obtained from a measurement of its dimensions. In the *c. g. s.* system, however, the principle of Archimedes furnishes a simple method of finding the volume of a solid, however irregular it may be; for in this system the volume of an immersed solid is numerically equal to its loss of weight in water (§ 63). Then the equation which defines density (§ 69),

$$density = \frac{mass}{volume},$$

becomes

$$density = \frac{mass\ of\ body}{loss\ of\ weight\ in\ water}.$$

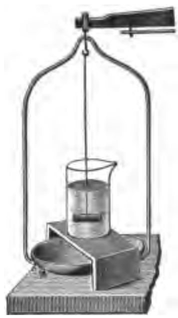


FIGURE 55. — SOLIDS HEAVIER THAN WATER.

73. Solids Heavier than Water. — Find the mass of the body in air in terms of grams; if it is insoluble in water, find its apparent loss of weight by suspending it in water (Fig. 55). This loss of weight is equal to the weight of the volume of water displaced by the solid (§ 63). But the volume of a body in cubic centimeters is the same as the mass in grams of an equal volume of water. The mass divided by this volume is the density.

74. Solids Lighter than Water. — If the body floats, its volume may still be obtained by tying to it a sinker heavy

enough to force it beneath the surface. Let w_1 denote the weight in grams required to counterbalance when the body is in the air, and the attached sinker in the water; and let w_2 denote the weight to counterbalance when both body and sinker are under water (Fig. 56). Then obviously $w_1 - w_2$ is equal to the upward force on the body alone, and is therefore numerically equal to the volume of the body. The mass divided by this volume is the density.

FIGURE 56. — SOLIDS LIGHTER THAN WATER.

If the solid is soluble in water, a liquid of known density, in which the body is not soluble, must be used in place of water. Then the loss of weight is equal to the weight of the liquid displaced, and if this is divided by the density of the liquid (Equation 2), the volume of the body will be obtained. Then the mass of the body divided by this volume will be the density sought.

EXAMPLES. — First, *for a body heavier than water.*

Weight of body in air	10.5 g.
Weight of body in water	6.3 g.
Weight of water displaced	4.2 g.

Since the density of water is 1 g. per cubic centimeter, the volume of the water displaced is 4.2 cm.^{3}. This is also the volume of the body. Therefore, $10.5 \div 4.2 = 2.5$ g. per cubic centimeter is the density.

Second, *for a body lighter than water.*

Weight of body in air	4.8 g.
Weight of sinker in water	10.2 g.
Weight of body and sinker in water . . .	8.4 g.

The combined weight of the body in air and the sinker in water is, then, $4.8 + 10.2 = 15$ g. But when the body is attached to the

sinker, their apparent combined weight is only 8.4 g. Therefore the buoyant effort on the body is $15 - 8.4 = 6.6$ g., and this is the weight of the water displaced by the body, and hence its volume is 6.6 cm.^{3}. The density is, then, $4.8 \div 6.6 = 0.73$ g. per cubic centimeter.

Third, *for a body soluble in water.* Suppose it is insoluble in alcohol, the density of which is 0.8 g. per cubic centimeter.

Weight of body in air	4.8 g.
Weight of body in alcohol	3.2 g.
Weight of alcohol displaced	1.6 g.

The volume of alcohol displaced is $1.6 \div 0.8 = 2$ cm.^{3}. This is also the volume of the body. Therefore, the density of the body is $4.8 \div 2 = 2.4$ g. per cubic centimeter.

75. Density of Liquids. — (*a*) *By the specific gravity bottle.* *A specific gravity bottle* (Fig. 57) is usually made to hold a definite mass of distilled water at a specified temperature, for example, 25, 50, or 100 g. Its volume is therefore 25, 50, or 100 cm.^{3}. To use the bottle, weigh it empty, and filled with the liquid, the density of which is to be determined. The weight of the liquid divided by the capacity of the bottle in cubic centimeters (the number of grams) is equal to the density of the liquid.

FIGURE 57. — SPECIFIC GRAVITY BOTTLE.

(*b*) *By the density bulb.* The *density bulb* is a small glass globe loaded with shot, and having a hook for suspension (Fig. 58). To use it, suspend from the arm of a balance with a fine platinum wire, and weigh first in air and then in water. The apparent loss of weight is the weight of the water displaced by the bulb. Then weigh it again when suspended in the liquid. The loss of weight is this time the weight of a volume of the

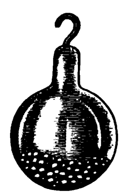


FIGURE 58. — DENSITY BULB.

liquid equal to that of the bulb. Divide this loss of weight by the loss in water, and the quotient will be the specific gravity of the liquid, or its density in grams per cubic centimeter (§ 71).

FIGURE 59. — HYDROMETER.

(*c*) ***By the hydrometer.*** The common ***hydrometer*** is usually made of glass, and consists of a cylindrical stem and a bulb weighted with mercury or shot to make it sink to the required level (Fig. 59). The stem is graduated, or has a scale inside, so that readings can be taken at the surface of the liquid in which the hydrometer floats. These readings give the densities directly, or they may be reduced to densities by means of an accompanying table. Hydrometers sometimes have a thermometer in the stem to indicate the temperature of the liquid at the time of taking the reading. Specially graduated instruments of this class are used to test milk, alcohol, acids, etc.

For liquids lighter than water, in which the hydrometer sinks to a greater depth, it is customary to use a separate instrument to avoid so long a stem and scale.

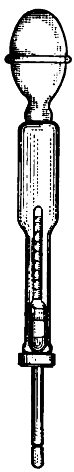


FIGURE 60. — ACID HYDROMETER.

For testing the acid of a storage battery, the hydrometer is inclosed in a large glass tube (Fig. 60). By means of the rubber bulb at the top of the large tube enough acid may be drawn in to make the hydrometer float. The hydrometer is then read as usual and the acid is returned to the cell by squeezing the bulb.

Questions and Problems

1. Why does an ocean steamer draw more water after entering fresh water?

2. If the Cartesian diver should sink in the jar, why will the addition of salt cause it to rise?

3. What is the density of a body weighing 15 g. in air and 10 g. in water? What is its specific gravity?

4. A hollow brass ball weighs 1 kg. What must be its volume so that it will just float in water?

5. What is the density of a body weighing 20 g. in air and 16 g. in alcohol whose density is 0.8 g. per cubic centimeter?

6. A bottle filled with water weighed 60 g. and when empty 20 g. When filled with olive oil it weighed 56.6 g. What is the density of olive oil?

7. A density bulb weighed 75 g. in air, 45 g. in water, and 21 g. in sulphuric acid. Calculate the density of the sulphuric acid.

8. A piece of wood weighs 96 g. in air, 172 g. in water with sinker attached. The sinker alone in water weighs 220 g. Find the density of the wood.

9. A piece of zinc weighs 70 g. in air, and 60 g. in water. What will it weigh in alcohol of density 0.8 g. per cubic centimeter?

10. The mark to which a certain hydrometer weighing 90 g. sinks in alcohol is noted. To make it sink to the same mark in water it must be weighted with 22.5 g. What is the density of the alcohol?

11. A body floats half submerged in water. What is its specific gravity? What part of it will be submerged in alcohol, specific gravity 0.8?

12. If an iron ball weighs 100.4 lb. in air, what will it weigh in water if its specific gravity is 7.8?

13. What is the specific gravity of a wooden ball that floats two thirds under water?

14. A ferry boat weighs 700 tons. What will be the displacement of water if it takes on board a train weighing 600 tons?

15. A liter flask weighing 75 g. is half filled with water and half with glycerine. The flask and liquids weigh 1205 g. What is the density of the glycerine? What is its specific gravity?

IV. PRESSURE OF THE ATMOSPHERE

76. Weight of Air. — It is only a little more than 250 years since it became definitely known that air has any weight at all. Even now we scarcely appreciate its weight.

Place a globe holding about a liter (Fig. 61) on the pan of a balance and counterpoise; the stopcock should be open. Remove the globe and force in more air with a bicycle pump, closing the stopcock to retain the air under the increased pressure; the balance will show that the globe is heavier than before. Remove it again and exhaust the air with an air pump; the balance will now show that the globe has lost weight. A large incandescent lamp bulb may be used in place of the globe by first counterbalancing and then admitting air by puncturing with the very pointed flame of a blowpipe. Thus air, though invisible, may be put into a vessel or removed like any other fluid; and, like any other fluid, it has weight.

FIGURE 61. — GLOBE FOR WEIGHING AIR.

The weight of a body of air is surprisingly large. A cubic yard of air at atmospheric pressure weighs more than 2 lb. The air in a hall 50 ft. long, 30 ft. wide, and 18 ft. high weighs more than a ton. Precise measurements have shown that air at the temperature of freezing and under a pressure equal to that of a column of mercury 76 cm. high weighs 1.293 g. per liter, or 0.001293 g. per cubic centimeter.

77. Pressure Produced by the Air. — Since the air surrounding the earth has weight, it must exert pressure on any surface equal to the weight of a column of air above it, just as in the case of a liquid. Many experiments prove this to be true. We are not aware of this pressure because it is equalized in all directions, and we are built to sustain it, just as deep-sea fishes sustain the much greater pressure of water above them.

Stretch a piece of sheet rubber, and tie tightly over the mouth of a glass vessel, as shown in Fig. 62. If the air is gradually exhausted from the vessel, the rubber will be forced down more and more by the pressure of the air above it, and it may break. The depression will be the same in whatever direction the rubber membrane may be turned.

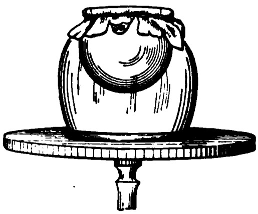


FIGURE 62. — DOWNWARD PRESSURE OF THE AIR.

Fill a common tumbler full of water, cover with a sheet of paper so as to exclude the air, and holding the hand against the paper, invert the tumbler (Fig. 63). When the hand is removed, the paper is held against the mouth of the glass with sufficient force to keep the water from running out.

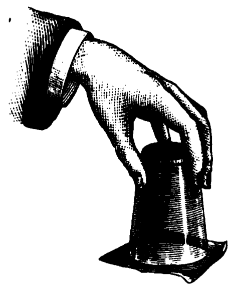


FIGURE 63. — UPWARD PRESSURE OF THE AIR.

Cut about 20 cm. from a piece of glass tubing of 3 or 4 mm. bore. Dip it vertically into a vessel of water, and close the upper end with the finger. The tube may now be lifted out, and the water will remain in it.

Figure 64 illustrates a pipette; it is useful for conveying a small quantity of liquid from one vessel to another.

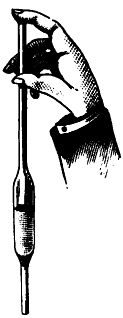


FIGURE 64. — PIPETTE.

78. The Rise of Liquids in Exhausted Tubes. — Near the close of Galileo's life his patron, the Duke of Tuscany, dug a deep well near Florence, and was surprised to find that he could get no pump in which water would rise more than about 32 feet above the level in the well. He appealed to Galileo for an explanation; but Galileo appears to have been equally surprised, for up to that time everybody supposed that water rose in tubes exhausted by suction because "nature abhors a vacuum." Galileo sug-

HYDRO-AËROPLANES.

When in the air these are sustained by the air-pressure against their planes; when on the water, by the water-pressure against their pontoons.

gested experiments to find out to what limit nature abhors a vacuum, but he was too old and enfeebled in health to perform them himself and died before the problem was solved by others.

79. Torricelli's Experiment. — Torricelli, a friend and pupil of Galileo, hit upon the idea of measuring the resistance nature offers to a vacuum by a column of mercury in a glass tube instead of a column of water in the Duke of Tuscany's pump. The experiment was performed in 1643 by Viviani under Torricelli's direction.

A stout glass tube about a yard long, sealed at one end and filled with clean mercury, is closed at the open end with the finger, and inverted in a vessel of mercury in a vertical position (Fig. 65). When the finger is removed, the column falls to a height of about 30 inches. The space above the mercury is known as a *Torricellian vacuum.* The column of mercury in the tube is counterbalanced by the pressure of the atmosphere on the mercury in the larger vessel at the bottom.

FIGURE 65. — TORRICELLI'S TUBE.

80. Pascal's Experiments. — To Pascal is due the credit of completing the demonstration that the weight of the column of mercury in the Torricellian experiment measures the pressure of the atmosphere. He reasoned that if the mercury is held up simply by the pressure of the air, the column should be shorter at higher altitudes because there is then less air above it. Put to the test by carrying the apparatus to the top of the Tour St. Jacques (Fig. 66), 150 feet high, at that time the bell tower of a church in Paris, his theory was confirmed. A statue of Pascal now stands at the

base of the old tower. Desiring to carry the test still further, he wrote to his brother-in-law to try the experiment on the Puy de Dôme, a mountain nearly 1000 m. high, in southern France. The result was that the column of mercury was found to be nearly 8 cm. shorter than in Paris.

FIGURE 66. — TOUR ST. JACQUES.

Pascal repeated the experiment with red wine instead of mercury, and with glass tubes forty-six feet long; and he found that the lighter the fluid, the higher the column sustained by the pressure of the air. Further, a balloon, half filled with air, appeared fully inflated when carried up a high mountain, and collapsed again gradually during the descent. Thus the question of the Duke of Tuscany was fully answered; liquids rise in exhausted tubes because of the pressure of the atmosphere on the surface of the liquid outside.

81. Pressure of One Atmosphere. — The height of the column of mercury supported by atmospheric pressure varies from hour to hour and with the altitude above the sea. Its height is independent of the cross section of the tube, but to find the pressure, or force per unit area, a tube of unit cross section must be assumed. Suppose an

internal cross-sectional area of 1 $cm.^2$. The standard height chosen is 76 cm. of mercury at the temperature of melting ice (0° C.), and at sea level in latitude 45°. The density of mercury at this temperature is 13.596 grams per cubic centimeter. Hence, *standard atmospheric pressure*, which is the weight of this column of mercury, is

$$76 \times 13.596 = 1033.3 \text{ g. per square centimeter, or roughly 1 kg. per square centimeter, equivalent to 14.7 lb. per square inch.}$$

The height of a column of water to produce a pressure of one atmosphere is $76 \times 13.596 = 1033.3$ cm. = 33.9 ft.

82. The Barometer. — The *barometer* is an instrument based on Torricelli's experiment, and is designed to measure the varying pressure of the atmosphere. In its simplest form it consists of a J-shaped glass tube about 86 cm. (34 in.) long, and attached to a supporting board (Fig. 67). The short arm has a pinhole near the top for the admission of air. A scale is fastened by the side of the tube, and the difference of readings at the top of the mercury in the long arm and the short one gives the height of the mercury column sustained by atmospheric pressure. This varies from about 73 to 76.5 cm. for places near sea level. When accuracy is required, the barometer reading must be corrected for temperature. A good barometer must contain pure mercury, and the mercury must be boiled in the glass tube to expel air and moisture.

FIGURE 67. — THE BAROMETER.

83. The Aneroid Barometer. — A more convenient barometer to carry about is the aneroid barometer, which contains no liquid. It consists essentially of a shallow cylindrical box (Fig. 68), from which the air is partially exhausted. It has a thin cover corrugated in circular ridges to give it greater flexibility. The cover is prevented from collapsing under atmospheric pressure by a stiff spring attached to the center of the cover (shown in the figure under the pointer). This flexible cover rises and falls as the pressure of the atmosphere varies, and its motion is transmitted to the pointer by means of delicate levers and a chain. A scale graduated by comparison with a mercurial barometer is fixed under the pointer. These instruments are so sensitive that they readily indicate the change of pressure when carried from one floor of a building to the next, or even when moved no farther than from a table to the floor.

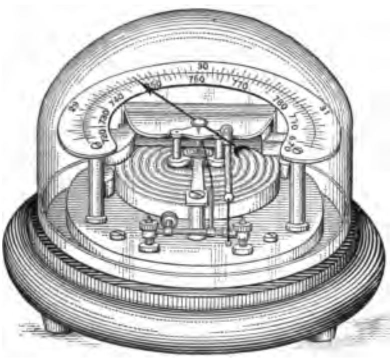


FIGURE 68. — ANEROID BAROMETER.

84. Utility of the Barometer. — The barometer is a faithful indicator of all changes in the pressure of the atmosphere. These may be due to fluctuations in the atmosphere itself, or to changes in the elevation of the observer.

The barometer is constantly used by the Weather Bureau in forecasting changes in the weather. Experience has shown that barometric readings indicate weather changes as follows :

I. *A rising barometer indicates the approach of fair weather.*

II. *A sudden fall of the barometer precedes a storm.*

III. *An unchanging high barometer indicates settled fair weather.*

The difference in the altitude of two stations may be computed from barometer readings taken at the two places simultaneously. Various complex rules have been proposed to express the relation between the difference in barometer readings and the difference in altitude; a simple rule for small elevations is to allow 0.1 in. for every 90 ft. of ascent.

85. Cyclonic Storms. — Weather maps are drawn from observations made at many places at the same time and telegraphed to a central station. In this way cyclonic storms are discovered and followed. At the center of the storm is the lowest reading of the barometer. Curves called *isobars* are traced through points of equal pressure around this center (Fig. 69). The wind blows from areas of higher pressure toward those of lower, but in the northern hemisphere the inflowing winds are deflected toward the right on account of the rotation of the earth. This gives to the storm a counter-clockwise rotation, as indicated by the arrows in a weather map. Cy-

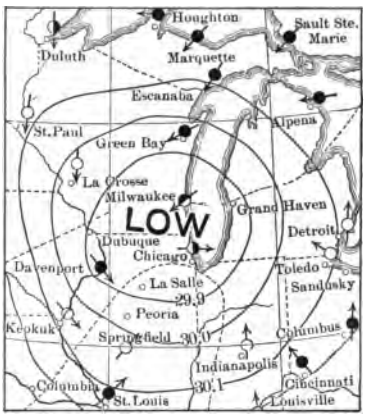


FIGURE 69. — ISOBARS.

clonic storms usually cross the northwest boundary of the United States from British Columbia, travel in a southeasterly direction until they cross the Rocky Mountain range, and then turn northeasterly toward the Atlantic coast. Storms coming from the Gulf of Mexico usually travel along the Atlantic coast toward the northeast.

Questions and Problems

1. Why is mercury the best liquid to use in a barometer?

2. What would be the effect of getting a little air in the top of a barometer tube?

3. Why are mercurial barometers always suspended from the top and never supported on a foot?

4. Does the height to which the mercury in a barometer tube rises depend on the diameter of the tube?

5. A tube 1 ft. long is closed at one end by a sheet of thin rubber tied over it air-tight. It is then filled with mercury and inverted in a vessel of mercury as in Torricelli's experiment. Why does the rubber membrane settle down into the tube?

6. A glass tube 1 ft. long is closed at one end, filled with mercury as in Torricelli's experiment, but, instead of resting on the bottom of the vessel, it is suspended from one arm of a balance. Does it weigh more than before it was filled? Give reason.

7. The barometer reading is 75.2 cm. Calculate the atmospheric pressure per square centimeter.

8. The barometer reading is 29 in. Calculate the atmospheric pressure per square inch.

9. Calculate the buoyancy of the air for a ball 10 cm. in diameter if a liter of air weighs 1.29 g.

10. The density of glycerine is 1.26 g. per cubic centimeter. If a barometer were constructed for glycerine, what would be its reading when the mercurial barometer reads 75 cm.?

11. When the density of the air is 0.0013 g. per cubic centimeter, how much less will 200 $cm.^3$ of cork weigh in air than in a vacuum?

12. If a barometer at the foot of a tower reads 29.5 in., while one at the top reads 29.2 in., what is the height of the tower?

13. A bottle is fitted air-tight with a rubber stopper and a tube as in Fig. 70. If water be sucked out by the tube, what will happen when the tube is released? If air is blown in through the tube, what will happen when the tube is released?

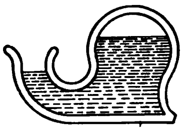


FIGURE 71.

14. Figure 71 represents a pneumatic inkstand, nearly full of ink. Why does the ink not run out?

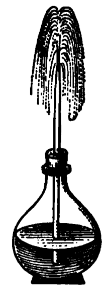


FIGURE 70.

V. COMPRESSION AND EXPANSION OF GASES

86. Compressibility of Air. — The inflation of a toy balloon, an air cushion, and a pneumatic tire illustrates the ready compressibility of the air.

Push a long test tube under water with its open end down. The deeper the tube is sunk, the higher the water rises in it and the smaller becomes the volume of the inclosed air; also the reaction tending to lift the tube increases.

The expansibility of air, or its tendency to increase in volume whenever the pressure is reduced, is shown by its escape from any vessel under pressure, such as the rush of compressed air from a popgun, an air gun, or a punctured pneumatic tire. The air in a building shows the same tendency to expand. When the pressure outside is suddenly reduced, as in the passage of a wave due to an explosion, the force of expansion of the air within often bursts the windows outward.

Blow air into the bottle (Fig. 70) through the open tube. The air forced in bubbles up through the water and is compressed within. As soon as the tube is released and the pressure in it falls to that of

the atmosphere, the expansive force of the imprisoned air forces water out through the tube with great velocity. This principle is applied in many forms of devices for spraying plants and shrubbery.

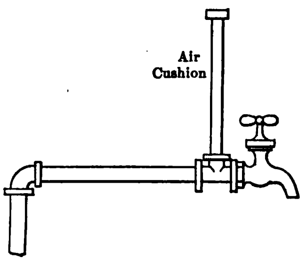


FIGURE 72. — AIR CUSHION ON WATER PIPE.

The compression and the expansion of air are both illustrated by the common pneumatic door check for light doors; also by the air dome on a force pump; and the air cushion on a water pipe (Fig. 72), which is usually carried a few inches higher than the faucet so that the air confined in the closed end may act as a cushion to take up any sudden shock due to the inertia of the water when the stream is suddenly checked. The "pounding" of the pipes when the water is turned off quickly is owing to the absence of this air cushion.

87. Boyle's Law. — In dealing with air in a state of compression or expansion, the question at once arises, — how does a given volume of air change when the pressure on the air changes? The answer is contained in the discovery by Robert Boyle at Oxford, England, in 1662. The principle discovered by Boyle (and later in France by Mariotte) is known as *Boyle's law; it applies to all gases at a constant temperature.*

Boyle in his experiments used a J-tube with the short arm closed; both arms were provided with a scale (Fig. 73). In his experiments the pressures extended only from $\frac{1}{24}$ of an atmosphere to 4 atmospheres.

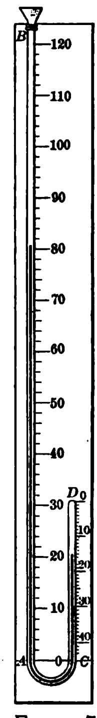


FIGURE 73. — BOYLE'S EXPERIMENT.

Mercury was poured in until it stood at the same level in both arms of the tube. The air in the short arm was then under the same pres-

sure as the atmosphere outside. Its volume was noted by means of the attached scale, and more mercury was then poured into the tube. The difference in the level of the mercury in the two arms of the tube gave the excess of pressure on the inclosed air above that of the atmosphere. When this difference amounted to 76 cm., the pressure on the gas in the short tube was 2 atmospheres, and its volume was reduced to one half. When the difference became twice 76 cm., the pressure on the inclosed air was 3 atmospheres and its volume became one third; and so on.

This is the law of the compressibility of gases; it may be expressed as follows:

At a constant temperature the volume of a given mass of gas varies inversely as the pressure sustained by it.

If the volume of gas v under a pressure p becomes volume v' when the pressure is changed to p', then by the law:

$$\frac{v}{v'} = \frac{p'}{p}; \text{ whence } pv = p'v'. \qquad \text{(Equation 3)}$$

(Notice the *inverse* proportion.) In other words, *the product of the volume of the gas and the corresponding pressure remains constant for the same temperature.*

88. The Law Approximate. — Extended investigations have shown that Boyle's law is not rigorously exact for any gas. In general, gases are more compressible than the law requires, and this is especially true for gases which are easily liquefied, such as carbon dioxide (CO_2), sulphur dioxide (SO_2), and chlorine. Within moderate limits of pressure, however, Boyle's law is exceedingly useful in dealing with the volume and pressure of gases.

An example will illustrate its use: If a mass of gas under a pressure of 72 cm.^{3} of mercury has a volume of 1900 cm.^{3}, what would its volume be if the pressure were 76 cm.^{3}? By Equation 3, $pv = p'v'$; hence, $72 \times 1900 = 76 \times v'$. From this equation $v' = 1800$ cm.^{3}.

89. The Air Compressor. — A pump designed to compress air or other gases under a pressure of several atmospheres is shown in section in Fig. 74, and complete in Fig. 75. The piston is solid, and there are two metal valves at the bottom. Air or other gas is admitted through the left-hand tube when the piston rises; when it descends, it compresses the inclosed air, the pressure closes the left-hand valve, and opens the outlet valve on the right, and the compressed air is discharged into the compression tank.

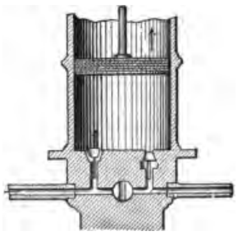


FIGURE 74. — SECTION OF AIR COMPRESSOR.

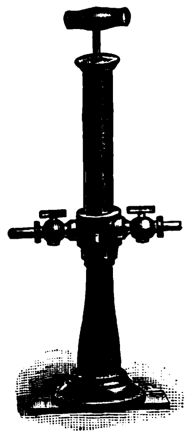


FIGURE 75. — AIR COMPRESSOR.

A bicycle pump (Fig. 76) is an air compressor of a very simple type. The piston has a cup-shaped leather collar *c*, which permits the air to pass by into the cylinder when the piston is withdrawn, but closes when the piston is forced in. The collar thus serves as a valve, allowing the air to flow one way but not the other. The compressed air is forced through the tube forming the piston rod, and the check valve in the tire inlet prevents its return.

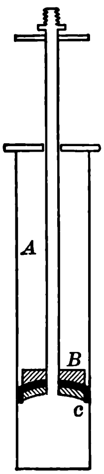


FIGURE 76. — BICYCLE PUMP.

90. The Air Pump. — The *air pump* for removing air or any gas from a closed vessel depends for its action on the expansive or elastic force of the gas. The first air pump was invented by Otto von Guericke, burgomaster of Magdeburg, about 1650.

In the very simplest form the two valves, corresponding with those of the air compressor, are worked by the pressure of the air. But though they may be made of oiled silk and very light, the pressure in the vessel to be exhausted soon reaches a lower limit below which it is too small to open the valve between it and the cylinder of the pump. On this account automatic valves, operated mechanically, are in use in the better class of pumps.

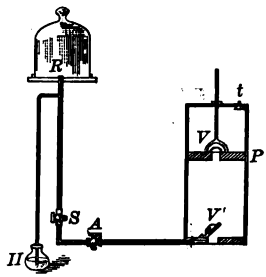


FIGURE 77. — SIMPLE AIR PUMP.

The modern pump in its simplest form is shown in Fig. 77. The two valves are operated by the pressure of the air; they are of oiled silk so as to be as light as possible. When the piston descends, valve V in the piston opens and V' at the bottom of the cylinder closes; the reverse is true when the piston ascends. The limit of exhaustion is reached when the elastic force of the rarefied air is not sufficient to open the valves.

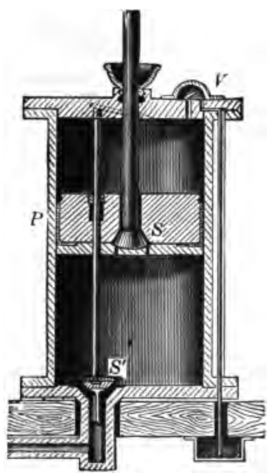


FIGURE 78. — AIR PUMP.

Figure 78 shows in section the cylinder of an air pump in which the valves are automatic. A piston P, with a valve at S, works in a cylindrical barrel, communicating with the outer air by a valve V at its upper end, and with the receiver to be exhausted by the horizontal tube at the bottom. The valve S' is carried by a rod passing through the piston, and fitting tightly enough to be lifted when the upstroke begins. The ascent of the rod is almost immediately

arrested by a stop near its upper end, and the piston then slides on the rod during the remainder of the upstroke. The open valve S' allows the air to flow from the vessel to be exhausted into the space below the piston. At the end of the upstroke the valve S' is closed by the lever shown in dotted lines. During the downward movement the valve S is open, and the inclosed air passes through it into the upper part of the cylinder. The ascent of the piston again closes S; and as soon as the air is sufficiently compressed, it opens the valve V and escapes. Each complete double stroke removes a cylinder full of air; but as it becomes rarer with each stroke, the mass removed each time is less.

FIGURE 79. — FOOTBALL UNDER RECEIVER.

FIGURE 80. — AFTER AIR IN RECEIVER IS EXHAUSTED.

91. Experiments with the Air Pump. — 1. *Expansibility of air.*

(*a*) *Football.* Fill a small rubber football half full of air, and place under a big bell jar on the table of the air pump (Fig. 79). When the air is exhausted from the jar, the football expands until it is free from wrinkles (Fig. 80). A toy balloon may be substituted.

FIGURE 81.—BOLTHEAD.

(*b*) *Bolthead.* A glass tube with a large bulb blown on one end (Fig. 81) is known as a *bolthead.* The stem passes air-tight through the cap of the bell jar, and dips below the surface of the water in the inner vessel. When the air is exhausted from the jar, the air in the bolthead expands and escapes in bubbles through the water. Readmission of air into the jar restores the pressure, and drives water into the bolthead. Why?

2. *Air pressure.* (*a*) *Downward.* Wet a piece of parchment paper, and tie it tightly over the mouth of a glass cylinder (Fig. 82). A

sheet of stout paper may be pasted over the cylinder instead. When the air is exhausted, the paper will break with a loud report.

FIGURE 83. — VACUUM FOUNTAIN.

(*b*) *The vacuum fountain.* A tall glass vessel has an inner jet tube which may be closed on the outside with a stopcock. Exhaust the air, place the opening into the jet tube in water, and open the stopcock. The water is forced by atmospheric pressure into the exhausted tube like a fountain (Fig. 83).

FIGURE 82. — BURSTING PARCHMENT PAPER.

(*c*) *Upward pressure.* A strong glass cylinder supported on a tripod is fitted with a piston (Fig. 84). The brass cover of the cylinder is connected with the air pump by a thick rubber tube. When the air is exhausted, the piston is lifted by atmospheric pressure, and carries the heavy attached weight.

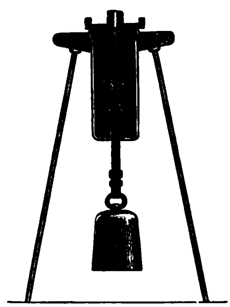


FIGURE 84. — LIFTING WEIGHT BY PRESSURE OF ATMOSPHERE.

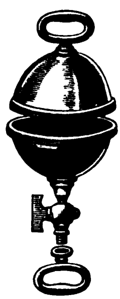


FIGURE 85. — MAGDEBURG HEMISPHERES.

(*d*) *The Magdeburg hemispheres.* This historical piece of apparatus was designed by Otto von Guericke to exhibit the great pressure of the atmosphere (Fig. 85). The lips of the two parts are accurately ground to make an air-tight joint when greased. When they are brought together and the air is exhausted, it requires considerable force to pull them apart. The original hemispheres of von Guericke were about 22 in. in diameter, and the atmospheric pressure holding them together was about 5600 lb.

92. Buoyancy of the Air. — A small beam balance has attached to one arm a hollow closed brass globe; it is counterbalanced in air by a solid brass weight on the other arm. When the balance is placed under a bell jar, and the air is exhausted, the globe overbalances the solid weight (Fig. 86).

FIGURE 86. — THE BAROSCOPE.

The apparatus just described is called a *baroscope*. It shows that the atmosphere exerts an upward or buoyant force on bodies immersed in it; that is, the principle of Archimedes applies to gases as well as to liquids. The buoyancy or lifting effect of the atmosphere is equal to the weight of the air displaced by a body. Whenever a body is less dense than the weights, it weighs more in a vacuum than in the air.

93. Balloons and *airships* also illustrate the buoyancy of the air. A soap bubble and a toy balloon filled with air fall because they are heavier than the air displaced; but if filled with hydrogen or coal gas, they rise in the air. Their buoyancy is greater than their weight, including the inclosed gas. The weight of a balloon with its car and contents must be less than that of the air displaced by it. The essential part of a balloon is a silk bag, varnished to make it air-tight; it is filled either with hydrogen or with illuminating gas. A cubic meter of hydrogen weighs about 0.09 kg.; a cubic meter of illuminating gas, 0.75 kg., while a cubic meter of air weighs 1.29 kg. With hydrogen the buoyancy is $1.29 - 0.09 = 1.2$ kg. per cubic meter; with illuminating gas it is $1.29 - 0.75 = 0.54$ kg. per cubic meter. The latter is more commonly used because it is much cheaper.

A balloon is not fully inflated to start with, but it expands as it rises because the pressure of the air on the outside diminishes. The buoyancy then decreases slowly as the balloon ascends into a rarer atmosphere. If it were fully inflated at the start, the inside pressure of

ENGLISH AIRSHIP CIRCLING ABOVE LONDON.

The church is St. Paul's Cathedral in the heart of London. Compare the shape of this airship with that of the German Zeppelin on page 82.

the gas at a high altitude would be greater than the outside atmospheric pressure, and the bag would burst.

Airships are balloons with steering and propelling devices attached. They are made of large volume so as to give them considerable lifting force. Huge Zeppelins have been made 775 feet long, and holding 32,000 cubic feet of gas. They are driven by several gasoline engines aggregating from 4000 to 5000 horsepower. Figure 87

is a picture of a Zeppelin with the outer rubberized cotton cloth *D* partly cut away, to show the gas balloons inside. *GG* are propellers, shown also in the front view in the corner of the picture. The balancing planes and the rudder may be seen at the rear end.

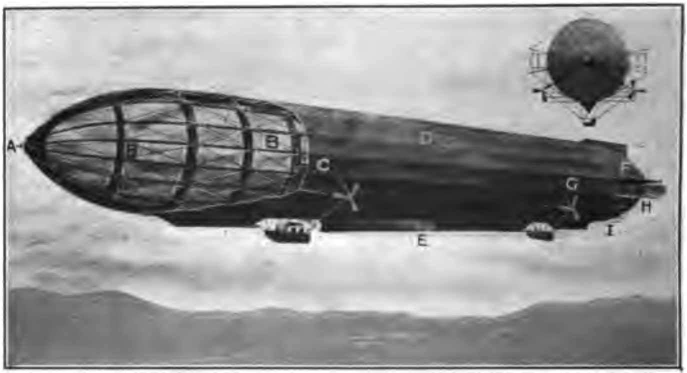


FIGURE 87. — A ZEPPELIN.

Problems and Questions

1. What limits the height to which a balloon will ascend?

2. A pound of feathers exactly counterpoises a pound of shot on the scale pans of a balance. Do they represent equal masses of matter? Explain.

3. What force will be required to separate a pair of Magdeburg hemispheres, assuming the air to be entirely removed from the inside, the diameter of the hemispheres being 4 in. and the height of the barometer 30 in.?

4. The volume of hydrogen collected over mercury in a graduated cylinder was 50 cm.^{3}, the mercury standing 15 cm. higher in the cylinder than outside of it. The reading of the barometer was 75 cm. How many cubic centimeters of hydrogen would there be at a pressure of 76 cm.?

SUGGESTION. The height of the mercury in the cylinder above the surface of the mercury outside must be subtracted from the barometer reading to get the pressure of the gas in the cylinder.

5. A test tube is forced down into water with its open end down, until the air in it is compressed into the upper half of the tube. How deep down is the tube if the barometer stands at 30 in.? (The specific gravity of mercury may be taken as 13.6.)

6. With what volume of illuminating gas must a balloon be filled in order to rise, if the empty balloon and its contents weigh 540 kg.?

7. A mass of iron, density 7.8, weighs 2 kg. in air. How much will it weigh in a vacuum?

VI. PNEUMATIC APPLIANCES

94. The Siphon. — The siphon is a U-shaped tube employed to transfer liquids from one vessel over an intervening elevation to another at a lower level by means of atmospheric pressure. If the tube is filled and is placed in the position shown in Fig. 88, the liquid will flow out of the vessel and be discharged at the lower level *D*.

FIGURE 88. — THE SIPHON.

If the liquid flows outward past the highest point of the tube in the direction *BC*, it is because the pressure on the liquid outward is greater than the pressure in the other direction. Now the outward pressure at the top is the pressure of the atmosphere transmitted by the liquid to the top minus the weight of the column of liquid *AB*; while the pressure inward is the atmospheric pressure transmitted to the top by the liquid in *BD* minus the weight of the column *DC*. Hence, the pressure inward is less than the pressure outward by the weight of a column of the liquid equal in height to the difference between *AB* and *DC*.

AB and *DC* are the lengths of the arms of the siphon. If the outer arm dips into the liquid in the receiving vessel,

the arm terminates at the surface of the liquid. To increase the length CD is to increase the rate of flow. As AB and DC approach equality the rate of flow decreases and the flow ceases when this difference is zero. The siphon fails to work also when B is about 33 feet above A. Why?

SIPHON OVER A MOUNTAIN

This would not work if the water had to be raised more than 33 feet on the other side of the mountain.

On a small scale siphons are used to empty bottles and carboys, which cannot be tilted to pour out a liquid; also to draw off a liquid from a vessel without disturbing the sediment at the bottom.

On a large scale engineers have used siphons for draining lakes and marshes; also for lifting water from the ocean or other large body of water through a pipe leading to a steam condenser in a power plant, whence it flows back through the return pipe to the level of the water supply. The pipes are continuous and air-tight, and the pump has no work to do except to keep the water running against friction in the pipes. There is also a slight back pressure because the water on the discharge side is warmer and therefore lighter than on the intake side.

When the mains of a water supply run over hills to a lower level, they constitute in reality siphons. Air is carried along with the water and collects in the bends at the tops. If there are several of these siphons one after another, the back pressure may actually stop

the flow of water, unless the air is removed by air pumps, or is allowed to escape under pressure through relief valves.

An *intermittent siphon* (Fig. 89) has its short arm inside a vase and its long arm passing through the bottom. The vase will hold water until its level reaches the top of the bend of the siphon. It then discharges and empties the vessel, if it discharges faster than it is filled. Again the water rises in the vase, and the siphon again empties it. Intermittent springs are supposed to operate on the same principle.

FIGURE 89. — INTERMITTENT SIPHON.

A *siphon fountain* may be made with a Florence flask and glass tubing (Fig. 90). The flask is partly filled with water, and the apparatus is then inverted as shown. The water enters the flask as a jet. If a piece of rubber tubing is attached to the longer arm, the jet will rise as the end of the tubing is lowered. A portion of the water runs out at first, producing a partial vacuum inside.

FIGURE 90. — SIPHON FOUNTAIN.

A *siphon in a vacuum* made of glass tubing about 2 mm. in diameter may be set up with mercury as the liquid. If it is set in action under a tall bell jar on the air pump, it will stop working when the air is exhausted from the jar, but will begin again when the air is admitted.

The *water in an S-trap*, in common use under sinks and washbowls, may be siphoned off when the discharge pipe is filled with water for a short distance below the trap, unless the trap is ventilated at the top of the S. Fig. 91 shows the method of ventilating such traps.

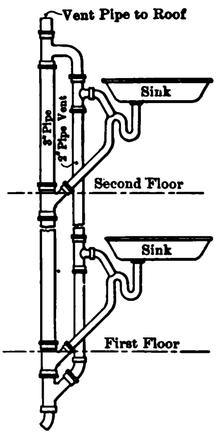


FIGURE 91. — VENTILATION OF S-TRAP.

95. The Lift Pump. — The common *lift* or *suction pump* acts by the pres-

sure of the air; it is, in fact, a simple form of air pump; but it was in use 2000 years before the air pump was invented. The first few strokes serve merely to draw out air from the pipe below the valve *V* (Fig. 92); the pressure of the air on the water in the well or cistern *W*, then forces it up the pipe *S*, and finally through the valve *V*. After that, when the piston descends, the valve *V* closes and checks the return of the water, and water passes through the valve *V'* above the piston. The next upstroke lifts the water to the level of the spout. Since the pressure of the air lifts the water to the highest point to which the piston ascends, it is obvious that this point cannot be more than the limit of about 33 ft. above the water in the well. Practically it is less on account of leakage through the imperfect valves. The priming of a pump by pouring in a little water to start it serves to wet the valves and make them air-tight.

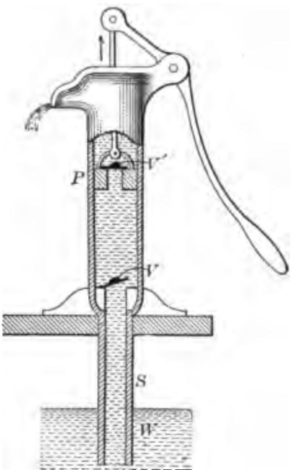


FIGURE 92. — SUCTION PUMP.

For deep wells the piston rod is lengthened and the valves *v* and *v'* are placed far down the well; the long pump rod serves to lift the water from the piston to the spout (Fig. 93).

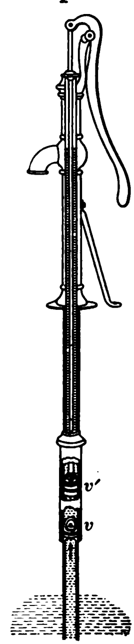


FIGURE 93. — LIFT PUMP.

96. The Force Pump. — The *force pump* (Fig. 94) is used to deliver water under pressure, either at a point

higher than the pump into pipes, as in the fire engine, into boilers against steam pressure, or into the cylinder of the hydraulic press.

The air dome *D* is added to secure a continuous flow through the delivery pipe *d*. Water flows out through *v'* only while the piston is descending; without the air dome, therefore, water would flow through the pipe *d* only during the downstroke of the piston; but the water under pressure from the piston enters the dome and compresses the air. The elastic force of the air drives the water out again as soon as *v'* closes. Thus the flow is practically continuous.

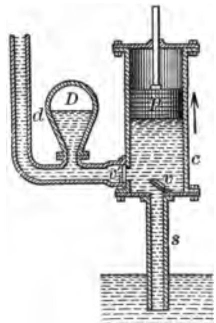


FIGURE 94. — FORCE PUMP.

The pump of a steam fire engine is double acting, that is, it forces water out while the piston is moving in either direction (Fig. 95); so also are pumps for waterworks and mines.

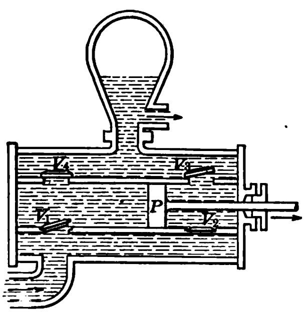


FIGURE 95. — FIRE ENGINE PUMP.

97. The Air Brake. — The well-known Westinghouse *air brake* is operated by compressed air. In Fig. 96 *P* is the train pipe leading to a large reservoir at the engine in which an air compressor maintains a pressure of about 75 lb. per square inch. So long as this pressure is applied through *P*, the automatic valve *V* maintains communication between *P* and an auxiliary reservoir *R* under each car, and at the same time shuts off air from the brake cylinder *C*. But as soon as the pressure in *P* falls, either by the movement of a lever in the engineer's cab or by the accidental parting of the hose coupling *k*, the valve *V* cuts off *P* and connects the reservoir *R* with the cylinder *C*. The pressure on the piston in *C* drives it powerfully

to the left and sets the brake shoes against the wheels. As soon as air from the main reservoir is again admitted to the pipe P, the valve V reëstablishes communication between P and R, and the confined air in C escapes. The brakes are released by the action of the spring S in forcing the piston back to the right.

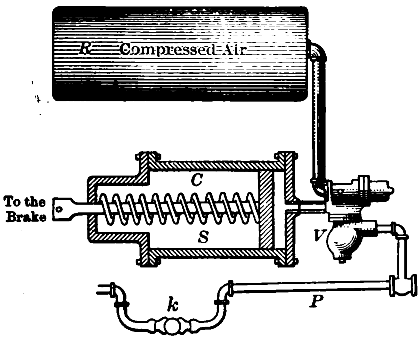


FIGURE 96.—AIR BRAKE.

98. Other Applications of the Air Pump and the Air Compressor. — The air pump and the air compressor are extensively used in industry. Sugar refiners employ the air pump to reduce the boiling point of the sirup by lowering the pressure on its surface in the evaporating pan; manufacturers of soda water use a compressor to charge the water with carbon dioxide; in pneumatic dispatch

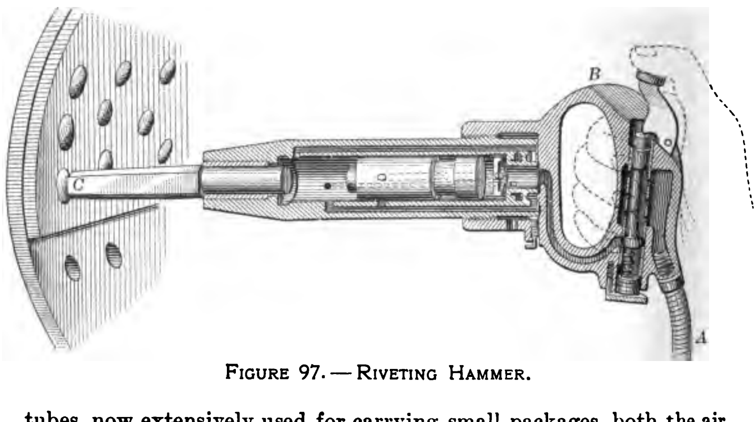


FIGURE 97.—RIVETING HAMMER.

tubes, now extensively used for carrying small packages, both the air pump and the compressor are used, one to exhaust the air from the tube in front of the closely fitting carriage, and the other to compress air in the tube behind it, so as to propel the carriage with great velocity. The air compressor is employed to make a forced draft for

steam boilers, to ventilate buildings, and to operate machinery in places difficult of access, as in mines, where it furnishes fresh air as well as power. It is employed also in the pneumatic *caisson* for making excavations and laying foundations under water. The caisson is a large heavy air chamber which sinks as the soft earth is removed from within. When its bottom is below water level, air is forced in under sufficient pressure to prevent the entrance of water. Access to it is gained by air-tight locks.

Compressed air is frequently used for operating railway signals, and to control automatic heating and ventilating appliances. Pneumatic tools are used for calking seams and joints, for stone cutting, chipping iron, and riveting. Figure 97 shows a riveting hammer; A is the air pipe, B the trigger for controlling the air, and C the hammer.

The *vacuum cleaner* is essentially a fan driven by an electric motor. The fan pushes the air away from one face and atmospheric pressure forces air through the mouthpiece of a tube leading to the fan to fill the partial vacuum. This stream of air carries with it the dust of the rug or carpet.

Questions and Problems

1. What will happen if the tip of an incandescent lamp bulb be broken off under water?

2. How can a tumbler of water be inverted (with the aid of a card) without spilling the water?

3. Explain why the "priming" of a dry suction pump restores it to working condition.

4. What sort of rubber tube must be used to connect a receiver to be exhausted by an air pump?

5. What is the limit of pressure to which a large suction water pump can subject the intake pipe? Will the pipe collapse if the pump "sucks" hard enough?

6. When the barometer stands at 29 in., what is the limiting height over which a siphon can carry water?

7. A vessel 36 in. deep is filled with mercury; can it be completely emptied by means of a siphon?

8. A diver works in 35 feet of sea water, specific gravity 1.025. What pressure must the compression pump supply to counterbalance the water pressure?

9. When the barometer reading is 73 cm., what is the greatest possible length of the short arm of a siphon when used for sulphuric acid, density 1.84 g. per cubic centimeter?

10. If the pressure against the 8 in. piston of an air brake is 80 lb. per square inch, what is the force driving the piston forward?

CHAPTER IV

MOTION

I. MOTION IN STRAIGHT LINES

99. All Motion Relative. — Rest and motion are relative terms only. A body is at rest when its relative position with respect to some point, line, or surface remains unchanged; but when that relative position is changing, the body is in motion.

The moving about of a person on a ship is relative to the vessel; the movement of the ship across the ocean is relative to the earth's surface; the daily motion of the earth's surface is relative to its axis of rotation; the motion of the earth as a whole is relative to the sun; while the sun itself is drifting with other stars through space.

100. Types of Motion. — Many familiar motions are irregular in every way, both as to direction and speed. The flight of a bird, the running of a boy at play, and even the motion of a man riding a horse, are illustrations. We shall study only those motions that can be classified and reduced to simple terms.

The line described by a moving body is its *path*. When this path is straight, like that of a falling body, the motion is *rectilinear;* when it is a curved line, like that of a rocket, the motion is *curvilinear*.

Then there is also *simple harmonic motion*, exemplified by the to-and-fro swing of a pendulum; and *rotary motion* about an axis, such as the rotation of the earth on its axis, and that of the pulley and armature of a stationary elec-

tric motor. The motion of a carriage wheel along a level road, and that of a ball along the floor of a bowling alley combine motion of rotation with rectilinear motion.

101. Speed or Velocity. — If an automobile runs thirty miles in an hour and a half, its average speed is 20 miles per hour. *Speed* or *velocity* is the *rate of motion*, that is, it is the distance traversed per unit of time. In expressing a speed or a velocity the time unit must be given as

THE TWENTIETH CENTURY LIMITED AT SIXTY MILES AN HOUR.
The railway train is one of our most familiar examples of motion.

well as the numerical value. Thus, 60 miles per hour, 5280 feet per minute, and 26.82 meters per second are all expressions for the same speed.

There is but little distinction between speed and velocity. Both express the rate of motion, but velocity is generally used to express the rate of motion in a definite direction, while speed is rate of motion without reference to direction.

102. Uniform Motion. — If the motion is over equal distances in equal and successive units of time, the motion is *uniform* and the velocity is *constant*. In uniform motion

the whole distance traversed is found by multiplying the speed by the time, or

$$distance = speed \times time.$$

In symbols this is written, $s = v \times t$; from which

$$v = \frac{s}{t} \text{ and } t = \frac{s}{v} \quad . \quad . \quad \text{(Equation 4)}$$

EXAMPLE. A railway train runs uniformly covering 660 ft. in 10 min. Then the speed $v = \frac{660}{10} = 66$ ft. per minute, or $\frac{3}{4}$ mi. per hour. The distance $s = 66 \times 10 = 660$ ft. The time $t = \frac{660}{66} = 10$ min.

The *average* speed in variable motion is found in the same way as in uniform motion, namely, by dividing the space traveled by the time.

103. Velocity at any Instant. — When the motion is variable, the velocity of a body *at any instant* is the distance it would travel in the next unit of time if at that instant its motion were to become *uniform*.

For example: The velocity of a falling body at any moment is the distance it would fall during the following second, *if the attraction of the earth and the resistance of the air were both to be withdrawn.* The velocity of a ball as it leaves the muzzle of a gun is the distance it would pass over in the second following *if from that instant it should continue to move for a second without any change in speed.* Actually the motion of the body and the ball for the succeeding second is *variable;* the question is, what would be the velocity if the motion were *invariable?*

104. Acceleration. — When a train runs a mile a minute for several minutes, it moves with uniform velocity; but when it is starting or slowing down, it is said to be *accelerated.* If the velocity increases, the acceleration is *positive;* if it decreases, it is *negative.* A falling body goes

faster and faster; it has a positive acceleration. A body thrown upward goes more and more slowly; it has a negative acceleration. A loaded sled starts from rest at the top of a long hill; it gains in velocity as it descends the hill; it has a positive acceleration. When it reaches the bottom, it loses velocity and is retarded, or has a negative acceleration, until it stops. *Acceleration is the rate of change of speed.*

Acceleration = change in speed per unit time.

Acceleration is always expressed as so many units of speed per unit of time. If, for example, a street car starting from rest gains uniformly in speed, so that at the end of ten seconds it has a speed of 10 miles per hour, its acceleration is its gain in speed-per-hour acquired in one second, or 1 mile-per-hour per second.

105. Uniform Acceleration. — If the change in velocity is the same from second to second, the motion is *uniformly accelerated.* The best example we have of uniformly accelerated motion is that of a falling body, such as a stone or an apple. Neglecting the resistance of the air, its gain in velocity is 9.8 m.-*per-second* for *every second it falls.* Its acceleration is therefore 9.8 m.-*per-second per second;* in other words, it gains in velocity 9.8 m.-*per-second* for *every second* of time. This is equivalent to an increase in velocity of 588 m.-*per-second* acquired in a *minute* of time. The unit of time enters twice into every expression for acceleration, the first to express the change in velocity, and the second to denote the interval during which this change takes place.

If an automobile starts from rest and increases its speed one foot a second for a whole minute, its velocity at the end of the minute is 60 ft. per second. Since it gains in one second a velocity of one foot

a second, and in one minute a velocity of 60 ft. a second, its acceleration may be expressed either as one foot-per-second per second, or as 60 ft.-per-second per minute. Its velocity is constantly changing; its acceleration is constant.

106. Velocity in Uniformly Accelerated Motion. — Suppose a body to move from rest in any given direction with a constant acceleration of 5 ft.-per-second per second. Its velocity at the end of the first second will be 5 ft. per second; at the end of two seconds, 2×5 ft.; at the end of three seconds, 3×5 ft.; and at the end of t seconds, $t \times 5$ ft. per second; that is,

$$\textit{final velocity} = \textit{time} \times \textit{acceleration},$$

or in symbols,

$$v = ta; \text{ whence } a = \frac{v}{t}. \quad . \quad \text{(Equation 5)}$$

Hence,

In uniformly accelerated motion the speed acquired in any given time is proportional to the time.

107. Distance traversed in Uniformly Accelerated Motion. — If we can find the *mean* or *average* velocity for any period of t seconds, the distance s traversed in t seconds may be found precisely as in the case of uniform motion (§ 102). For a body starting from rest with an acceleration of 5 feet-per-second per second, for example, its velocity at the end of four seconds is 4×5 ft. per second, and the average velocity for the four seconds is the mean between 0 and 4×5, or 2×5 ft. per second, the velocity at the middle of the period. So at the end of t seconds the average velocity is $\frac{1}{2}ta$ ft. per second. Then we have

$$\textit{distance} = \textit{average velocity} \times \textit{time},$$

or in symbols, $s = \frac{1}{2}\, ta \times t = \frac{1}{2}\, at^2$. . (Equation 6)

Hence,

In uniformly accelerated motion the distance traversed from rest is proportional to the square of the time.

108. Uniformly Accelerated Motion Illustrated. — The oldest method of demonstrating uniformly accelerated motion was devised by Galileo. It consists of an inclined plane two or three meters long (Fig. 98), made of a straight board with a shallow groove, down which a marble or a steel ball may roll slowly enough to permit the distances to be noted. For measuring time, a clock beating seconds, or a metronome, may be used. Assume a metronome as shown in the figure adjusted to beat seconds. One end of the board should be elevated until the ball will roll from a point near the top to the bottom in three seconds.

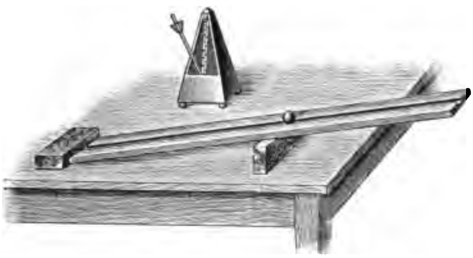


FIGURE 98. — GALILEO'S INCLINED PLANE.

Hold the ball in the groove against a straightedge in such a way that it may be quickly released at a click of the metronome. Find the exact position of the straightedge near the top of the plane from which the ball will roll to the bottom and strike the block there so that the blow will coincide with the third click of the metronome after the release of the ball. Measure exactly the distance between the upper edge of the straightedge and the block at the bottom and call it 9 *d*. Next, since distances are proportional to the square of the times, let the straight-

edge be placed at a distance of 4 *d* from the block; the ball released at this point should reach the block at the second click of the metronome after it starts. Finally, start the ball against the straightedge at a distance *d* from the block; the interval this time should be that of one beat of the metronome.

TABULAR EXHIBIT

NUMBER OF BEATS, t	WHOLE DISTANCE FALLEN, s	DISTANCE IN SUCCESSIVE INTERVALS	VELOCITIES ATTAINED, v
1	d	d	$2\ d$
2	$4\ d$	$3\ d$	$4\ d$
3	$9\ d$	$5\ d$	$6\ d$
4	$16\ d$	$7\ d$	$8\ d$

The third column is derived by subtracting the successive numbers of the second. To get the fourth column, we notice that if t is one second in Equation 6, then $s = \frac{1}{2}\ a$; that is, *the distance traversed in the first second is one half the acceleration.* But the acceleration is the same as the velocity acquired the first second. Hence $s = \frac{1}{2} v$ and $d = \frac{1}{2}\ v$. Therefore the velocity at the end of the first second on the inclined plane is $2\ d$. Since by Equation 5 the velocities are proportional to the time, the succeeding velocities are $4\ d$, $6\ d$, etc.

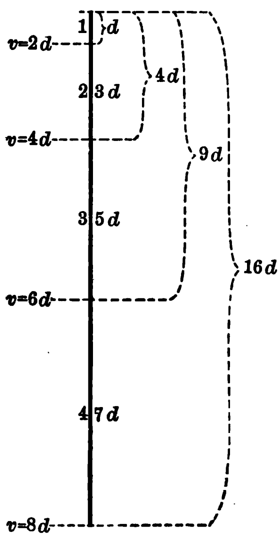


FIGURE 99. — LAWS OF FALLING BODIES.

The numbers in the second

column show that the distances traversed are proportional to the squares of the time [compare Equation 6]; those of column three show that the distances in successive seconds are as the odd numbers 1, 3, 5, etc. The results are shown graphically in Fig. 99.

Problems

NOTE. For the relation between the circumference of a circle and its diameter, see the Mensuration Table in the Appendix.

1. An aviator drives his aëroplane through the air a distance of 500 km. in 8 hr. 20 min. What was his average speed per minute?

2. The engine drives a boat downstream at the rate of 15 mi. an hour, while the current runs 3 ft. a second. How long will it take to go 50 mi.?

3. A man runs a quarter of a mile in 48.4 seconds. At that speed, what was his time for 100 yd.?

4. If a man can run 100 yd. in 10 sec., what would be his time for a mile, if it were possible to maintain the same speed?

5. A procession 100 yd. long, moving at the rate of 3 mi. an hour, passes over a bridge 120 yd. long. How long does it take the procession to pass entirely over the bridge?

6. An express train is running 60 mi. an hour. If the train is 500 ft. long, how many seconds will it be in passing completely over a viaduct 160 ft. in length?

7. A locomotive driving wheel is 2 m. in diameter. If it makes 200 revolutions per minute, what is the speed of the locomotive in kilometers per hour, assuming no slipping of the wheel on the track?

8. An automobile running at a uniform speed of 25 mi. per hour is 10 mi. behind another one on the same highway running 20 mi. per hour. How long will it take the former to overtake the latter, and how far will each machine have gone during this time?

9. If the acceleration of a marble rolling down an inclined plane is 40 cm.-per-second per second, what will be its velocity after 3 sec. from rest?

10. How far will a marble travel down an inclined plane in 3 sec. if the acceleration is 40 cm.-per-second per second?

11. A body starts from rest, and moving with uniformly accelerated motion acquires in 10 sec. a velocity of 3600 m. per minute. What is the acceleration per-second per second. How far does the body go in 10 sec.?

12. What acceleration per-minute per minute does a body have if it starts from rest and moves a distance of a mile in 5 min.? What will be its velocity at the end of 4 minutes?

13. If a train acquires in 2 min. a velocity of 60 mi. an hour, what is its acceleration per-minute per minute, assuming uniformly accelerated motion?

14. An electric car starting from rest has uniformly accelerated motion for 3 min. At the end of that time its velocity is 27 km. an hour. What is its acceleration per-minute per minute?

15. A sled is pushed along smooth ice until it has a velocity of 4 m. per second. It is then released and goes 100 m. before it stops. If its motion is uniformly retarded, what is the retardation in centimeters-per-second per second?

16. To acquire a speed of 60 mi. an hour in 10 min., how far would an express train have to run, provided it started from rest and its motion were uniformly accelerated?

II. CURVILINEAR MOTION

109. Direction of Motion on a Curve. — *Curvilinear motion*, or *motion along a curved line*, occurs more frequently in nature than motion in a straight line. The motion of a point on the earth's surface and about its axis is in a circle; the motion of the earth in its path around the sun is along a curve only approximately circular; the motion of a rocket or of a stream of water directed obliquely upward is along a parabolic curve. So also is the motion of a baseball when batted high in air. The thrown "curved ball," too, illustrates curvilinear motion.

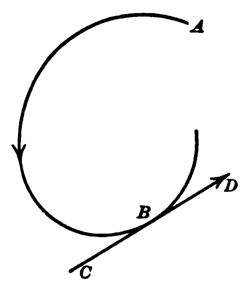


FIGURE 100. — MOTION ALONG A CURVE.

When the motion is along a curved line, the direction of motion *at any point*, as at B (Fig. 100), is that of the line CD, tangent to the curve at the point. This is the same as the direction of the curve at the point.

110. Uniform Circular Motion. — In uniform circular motion the velocity of the moving body, measured along the circle, is constant. There is then no acceleration in the direction in which the body is going at any point. But while the velocity remains unchanged in value, *it varies in direction.* If a body is moving with constant velocity in a straight line, its acceleration is zero *in every direction;* but *if the direction of its motion changes continuously*, then there is an acceleration *at right angles to its path* and its motion becomes *curvilinear.* If this acceleration is constant, the motion is uniform in a circle. Hence, *in uniform circular motion there is a constant acceleration directed toward the center of the circle.* It is called *centripetal acceleration.*

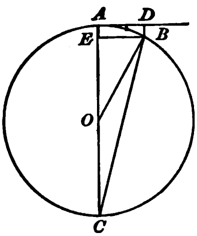


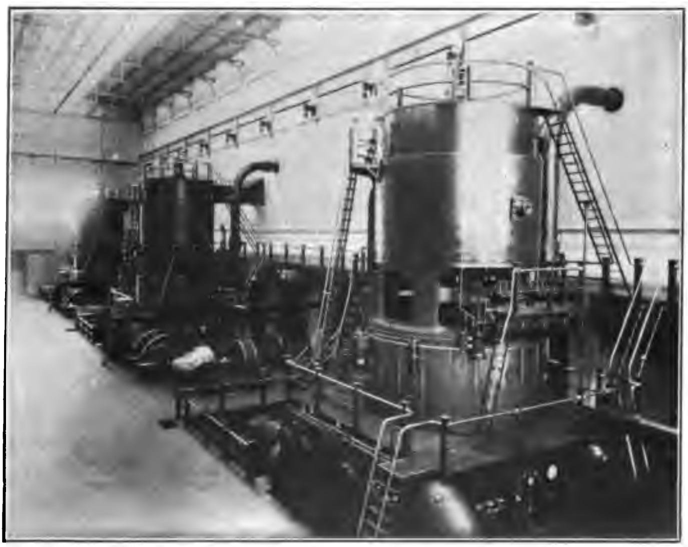
FIGURE 101. — CENTRIPETAL ACCELERATION.

Uniform circular motion consists of a uniform motion in the circumference of the circle and a uniformly accelerated motion along the radius. If v is the uniform velocity around the circle whose radius is r, the value of the *centripetal acceleration* is

$$a = \frac{v^2}{r}, * \quad . \quad . \quad . \quad . \quad \text{(Equation 7)}$$

or *centripetal acceleration* $= \dfrac{\textit{square of velocity in circle}}{\textit{radius of circle}}.$

* Let ABC (Fig. 101) be the circle in which the body revolves, and AB the minute portion of the circular path described in a very small interval of time t. Denote the length of the arc AB by s. Then, since



MOTION AND FORCE.

Above: White Star Liner "Britannic."
Below: Part of Boston Elevated Company's Power Plant.

III. SIMPLE HARMONIC MOTION

111. Periodic Motion. — The motion of a body is said to be *periodic* when it goes through the same series of movements in successive equal periods of time. It is *vibratory* if it is periodic and reverses its direction of motion at the end of each period. The motion of the earth around the sun is periodic, but not vibratory. A hammock swinging in the wind, the pendulum of a clock, a bowed violin string, and the prong of a sounding tuning fork illustrate both periodic and vibratory motion.

112. Simple Harmonic Motion. — Suspend a ball by a long thread and set it swinging in a horizontal circle (Fig. 102). Place a white screen back of the ball and a strong light, such as an arc light or a Welsbach gas light, at a distance of twelve or fifteen feet in front and on a level with the ball. Viewed in a darkened room, a shadow of the ball will be seen on the screen, moving to and fro in a straight line. This motion is very nearly *simple harmonic* and would be perfectly so if the projection could be made with sunlight, so that the projecting rays were perpendicular to the screen.

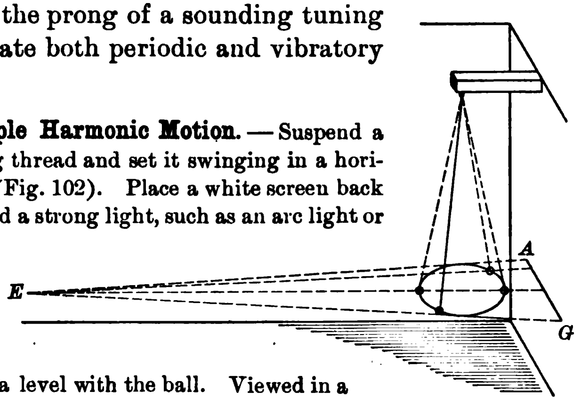


FIGURE 102. — SIMPLE HARMONIC MOTION.

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the motion along the arc is uniform, $s = vt$. AB is the diagonal of a very small parallelogram with sides AD and AE. The latter is the distance through which the revolving body is deflected toward the center while traversing the *very small arc* AB. Since the acceleration is constant, $AE = \frac{1}{2}at^2$ by Equation 6. The two triangles ABE and ABC are similar. Hence $\overline{AB}^2 = AE \times AC$. Calling the radius of the circle r and substituting for AB, AE, and AC their values, $v^2t^2 = \frac{1}{2}at^2 \times 2r = at^2r$. Then $a = \frac{v^2}{r}$.

Simple harmonic motion is the projection of a uniform circular motion on a straight line in the plane of the circle. All pendular motions of small arc are simple harmonic. The name appears to be due to the fact that simple musical sounds are caused by bodies vibrating in this manner.

The graph of a simple harmonic motion is obtained as follows: Draw the circle *adgk* (Fig. 103) representing the path of the ball, and the straight line *ADG* its projection on the screen. Divide the circumference into any even number of equal parts, as twelve. Through the points of division let fall perpendiculars on *AG*, as *aA*, *bB*, *cC*, etc. Now as the ball moves along the arc *adg*, its shadow appears to the observer to move from *A* through *B*, *C*, etc., to *G*, where it momentarily comes to rest. It then starts back toward *A*, at first slowly, but with increasing velocity until it passes *D*. Its velocity then decreases, and at *A* it is again zero, and its motion reverses.

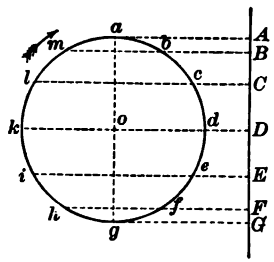


FIGURE 103. — GRAPH SIMPLE HARMONIC MOTION.

The radius of the circle, or the distance *AD*, is the *amplitude* of the vibration. The *period* of the motion is the time taken by the ball to go once around the circle ; it is the same as the time of a double oscillation of the projected motion. The *frequency* of the vibration is the reciprocal of the period. For example, if the period is $\frac{1}{2}$ a second, the frequency is 2, that is, two complete vibrations per second. This relation finds frequent illustration in musical sounds, where pitch depends on the frequency ; in light, where frequency determines the color ; and in alternating currents of electricity, where a frequency of 50, for example, means that a complete wave is produced every fiftieth of a second, and that the current reverses 100 times per second.

Two simple harmonic motions of the same period are said to differ *in phase* when they pass through their maximum or minimum velocities at a different time. Thus, if one has its maximum velocity at the same instant that the other has its minimum, the two motions differ in phase by a quarter of a period.

Problems

1. At what speed must an automobile be driven to go four times around a circular track one mile in diameter in thirty minutes?

2. The equatorial diameter of the earth is about 8000 miles. What is the speed in miles per minute of a point on the equator, owing to the earth's rotation on its axis?

3. A conical pendulum swinging in a circle whose diameter is 50 cm. makes 5 complete revolutions in 15 seconds. What is the centripetal acceleration of the bob?

4. The radius of the moon's orbit is 240,000 miles, and the moon revolves around the earth in 27 days, 8 hours. What is its centripetal acceleration with respect to the earth in feet-per-second per second?

5. A balance wheel on a stationary engine is 10 ft. in diameter and makes 100 revolutions per minute. A point on its circumference has what centripetal acceleration per-second per second?

6. The earth's equatorial radius is 20,926,000 feet, and the period of the earth's rotation on its axis is 23 h., 56 min., 4 sec. Calculate the the centripetal acceleration per-second per second at the equator.

CHAPTER V

MECHANICS OF SOLIDS

I. MEASUREMENT OF FORCE

113. Force. — A preliminary definition of force as a push or a pull has already been given. The effects of force in producing motion are among our commonest observations.

FRONT VIEW OF BRITISH "TANK."

Though the "tank" proceeds slowly, it exerts such force as to break down trees, walls, and even small buildings.

A brick loosened from a chimney or pushed from a scaffold falls by the force of gravity ; a mountain stream rushes down by reason of the same force in nature; the leaves of a tree rustle in the breeze, the branches sway violently in the wind, and their trunks are even twisted off by the

force of the tornado; powder explodes in a rifle and the bullet speeds toward its mark; loud thunder makes the earth tremble and vivid lightning rends a tree or shatters a flagstaff. From many such familiar facts is derived the conception that *force is anything that produces motion or change of motion* in material bodies. It remains now to explain how force is measured.

114. Units of Force. — Two systems of measuring force in common use are the *gravitational* and the *absolute.* The gravitational unit of force is the *weight* of a standard mass, such as the *pound of force*, the *gram of force*, or the *kilogram of force.* A pound of force means one equal to the force required to lift the mass of a pound against the downward pull of gravity. The same is true of the metric units with the difference in the mass lifted.

Gravitational units of force are not strictly constant because the weight of the same mass varies from point to point on the earth's surface, and at different elevations. The actual force necessary to lift the mass of a pound at the poles of the earth is greater than at the equator; it is less on the top of a high mountain than in the neighboring valleys, and still less than at the level of the sea. Gravitational units of force are convenient for the common purposes of life and for the work of the engineer, but they are not suitable for precise measurements, especially in the domain of electricity.

The so-called "absolute" unit of force in the *c.g.s.* system is the *dyne* (from the Greek word meaning *force*). *The dyne is the force which imparts to a gram mass an acceleration equal to one centimeter-per-second per second.* This unit is invariable in value, for it is independent of the variable force of gravitation. It is indispensable in framing the definitions of modern electrical and magnetic units.

115. Relation between the Gram of Force and the Dyne. — The *gram of force* is the pull of the earth on a mass of one gram, definitely at sea level and latitude 45°. Since the attraction of the earth in New York imparts to a gram mass an acceleration of 980 cm.-per-second per second, while the *dyne* produces an acceleration of only 1 cm.-per-second per second, it follows that the gram of force in New York is equal to 980 dynes, or the dyne is $\frac{1}{980}$ of the gram of force. The pull of gravity on a gram mass in other latitudes is not exactly the same as in New York, but for the purposes of this book it will be sufficiently accurate to say that *a gram of force is equal to* 980 *dynes.* It will be seen, therefore, that the value of any force expressed in dynes is approximately 980 times as great as in grams of force. Conversely, to convert dynes into grams of force, divide by 980.

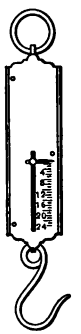


FIGURE 104. — SPRING BALANCE.

116. How a Force is Measured Mechanically. — The simplest device for measuring a force is the spring balance (Fig. 104). The common draw scale is a spring balance graduated in pounds and fractions of a pound. If a weight of 15 lb., for example, be hung on the spring and the position of the pointer be marked, then any other 15 lb. of force will stretch the spring to the same extent in any direction. If a man by pulling in any direction stretches a spring 3 in., and if a weight of 150 pounds also stretches the spring 3 in., the force exerted by the man is 150 pounds of force.

The spring balance may be graduated in pounds of force, kilograms or grams of force, or in dynes. If correctly graduated in dynes, it will give right readings at any latitude or elevation. Why are the divisions of the scale equal?

117. Graphic Representation of a Force. — A force has not only *magnitude* but also *direction;* in addition, it is often necessary to know its *point of application.* These three particulars may be represented by a straight line drawn through the point of application of the force in the direction in which the force acts, and as many units in length as there are units of force, or some multiple or submultiple of that number. If a line 1 cm. long stands for a force of 15 dynes, a line 4 cm. long, in the direction *AB* (Fig. 105), will represent a force of 60 dynes acting in the direction from *A* to *B*. Any point on the line *AB* may be used to indicate the point at which the force is applied.

FIGURE 105. — TO REPRESENT A FORCE.

If it is desired to represent graphically the fact that two forces act on a body at the same time, for example, 4 kg. of force horizontally and 2 kg. of force vertically, two lines are drawn from the point of application *A* (Fig. 106), one 2 cm. long to the right, and the other 1 cm. long toward the top of the page. The lines *AB* and *AC* represent the forces in point of application, direction, and magnitude, on a scale of 2 kg. of force to the centimeter.

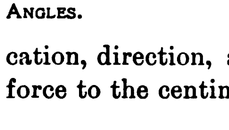


FIGURE 106. — TWO FORCES AT RIGHT ANGLES.

II. COMPOSITION OF FORCES AND OF VELOCITIES

118. Composition of Forces. — The *resultant* of two or more forces is a single force which will produce the same effect on the motion of a body as the several forces acting together. (Note the exception in the case of a couple, § 121.) *The process of finding the resultant of two or more*

forces is known as the composition of forces. It will be convenient to consider first the composition of parallel forces, and then that of forces acting at an angle. The several forces are called *components.*

119. The Resultant of Parallel Forces. — Suspend two draw scales, A and B (Fig. 107), from a suitable support by cords. Attach to them a graduated bar and adjust the draw scales and the attached cords so that they are vertical. Read the scales, then attach the weight W and again read the scales. Note the distances CE and ED. Correct each draw scale reading by subtracting from it the reading before the weight W was added. Compare W with the sum of these corrected readings, and also the ratio of the corrected readings of A and B to that of ED and EC.

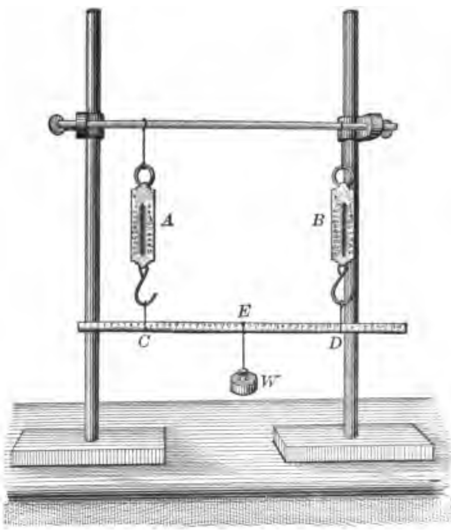


FIGURE 107. — PARALLEL FORCES.

Change the position of E and repeat the observations. It will be found in each case that $\frac{A}{B} = \frac{ED}{EC}$. Hence the following principle:

The resultant of two parallel forces in the same direction is equal to their sum; its point of application divides the line joining the points of application of the two forces into two parts which are inversely as the forces.

120. Equilibrium. — If two or more forces act on a body and no motion results, the forces are said to be in *equi-*

librium. In Fig. 107 the weight W is equal and opposite to the resultant of the two forces measured by the draw scales A and B. The three forces A, B, and W are in equilibrium. Further, each force is equal and opposite to the resultant of the other two and is called their *equilibrant.* The equilibrium of a body does not mean that its velocity is zero, but that its acceleration is zero. *Rest means zero velocity; equilibrium, zero acceleration.*

121. Parallel Forces in Opposite Directions. — If two parallel forces act in opposite directions, their resultant is their difference, and it acts in the direction of the larger force. In Fig. 107 the resultant of A and W is equal and opposite to B.

When the two parallel forces acting in opposite directions are *equal*, they form a *couple.* The resultant of a couple is zero; that is, no single force can be substituted for it and produce the same effect. A couple produces motion of rotation only, in which all the particles of the body to which it is applied rotate in circles about a common axis. For example, a magnetized sewing needle floated on water is acted on by a couple when it is displaced from a north-and-south position. One end of the needle is attracted toward the north, and the other toward the south, with equal and parallel forces. The effect is to rotate the needle about a vertical axis until it returns to a north-and-south position. The common auger, as a carpenter employs it to bore a hole, illustrates a couple in the equal and opposite parallel forces applied by the two hands.

122. The Resultant of Two Forces Acting at an Angle. — Tie together three cords at D (Fig. 108) and fasten the three ends to the hooks of the draw scales A, B, C. Pass their rings over pegs set in a board at such distances apart that the draw scales will all be

stretched. Record the readings of the scales, and by means of a protractor (see Appendix I) measure the angles formed at *D* by the cords. Draw on a sheet of paper three lines meeting at a point *D*, and forming with one another these angles. Lay off on the three lines on some convenient scale, distances to represent the readings of the draw scales, *DF* for *A*, *DE* for *B*, and *DC* for *C*. With *DF* and *DE* as adjacent sides, complete the parallelogram *DFGE* and draw the diagonal *DG*. *DG* is the resultant of the forces *A* and *B*, and its

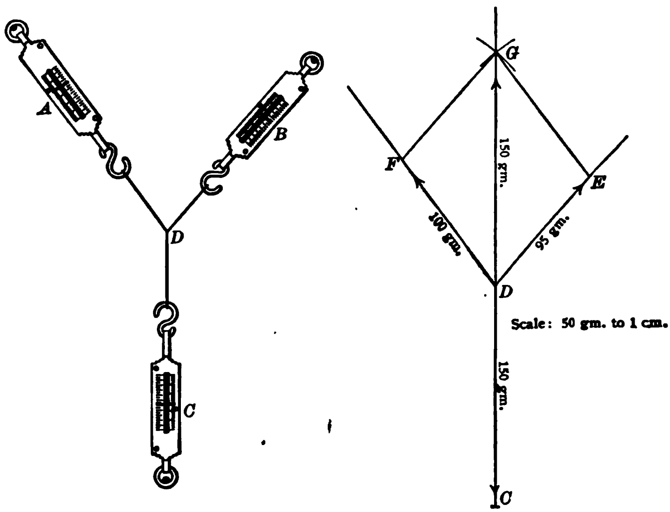


FIGURE 108. — RESULTANT OF TWO FORCES AT AN ANGLE.

length on the scale chosen will be found equal to that of *DC*, their equilibrant. Here again, each force is equal and opposite to the resultant of the other two.

When two forces act together on a body at an angle, the resultant lies between the two; its position and value may be found by applying the following principle, known as the *parallelogram of forces:*

If two forces are represented by two adjacent sides (DF and DE) of a parallelogram, their resultant is represented by the diagonal (DG) of the parallelogram drawn through their common point of application (D).

When the two forces are equal, their resultant lies midway between them. If the two forces are at right angles (Fig. 109) the parallelogram becomes a rectangle and the two forces and their resultant are represented by the three sides of a right triangle, *AB*, *BD*, *AD*. The value of the resultant in this case may be found by computing the hypotenuse of the triangle.

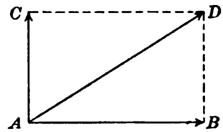


FIGURE 109. — FORCES AT RIGHT ANGLES.

For example, if the forces at right angles are 6 kg. of force and 8 kg. of force, their resultant is

$$\sqrt{6^2 + 8^2} = 10 \text{ kg. of force.}$$

123. Component of a Force in a Given Direction. — It frequently occurs that if a force produces any motion, it must be in a direction other than that of the force itself. For example, suppose the force *AB* (Fig. 110) applied to cause a car to move along the rails *mn*. The force *AB* evidently produces two effects; it tends to move the car along the rails, and it increases the pressure on them. The two effects are produced by the two forces *CB* and *DB* respectively. They are therefore the equivalent of *AB*. The force *CB* is called the component of *AB* in the direction of the rails *mn*, and *DB* is the component perpendicular to them. *The component of a force in a given direction is its effective value in this direction.*

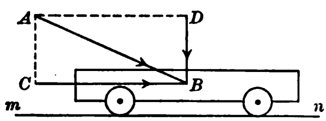


FIGURE 110. — COMPONENT IN GIVEN DIRECTION.

To find the component in a given direction, construct on the line representing the force, as the diagonal, a rectangle, the sides of which are respectively parallel and perpendicular to the direction of the required component; the length of the

side parallel to the given direction represents the component sought.

EXAMPLE. Let a force of 200 lb. be applied to a truck, as AB in Fig. 110; and let it act at an angle of 30° with the horizontal. Find the horizontal component pushing the truck forward.

Construct a parallelogram on some convenient scale (Appendix I) with the angle ABC equal to 30° and AB representing 200 lb. Measure the side CB and obtain by the scale used its equivalent in pounds of force. CB may be calculated since ACB is a right triangle. Since ABC is an angle of 30°, AC is one half of AB. Then, since AC denotes 100 lb. of force,

$$CB = \sqrt{\overline{AB}^2 - \overline{AC}^2} = \sqrt{200^2 - 100^2} = 173.2 \text{ lb. of force.}$$

124. Illustrations of the Resolution of a Force. — The kite, the sailboat, and the aëroplane are familiar illustrations of the resolution of the force of the wind.

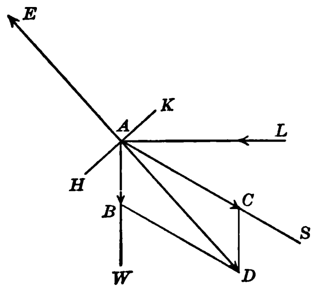


FIGURE 111. — FORCES ACTING ON KITE.

In the case of the kite, the forces acting are the weight of the kite AB (Fig. 111), the pull of the string AC, and the force of the wind LA. AD is the resultant of AB and AC. Resolve the force of the wind into two components, one perpendicular to HK, the face of the kite, and the other parallel to HK. If HK sets itself at such an angle that the component of LA perpendicular to HK coincides with AD and is equal to it, the kite will be in equilibrium; if it is greater than AD, the kite will move upward; if less, it will descend.

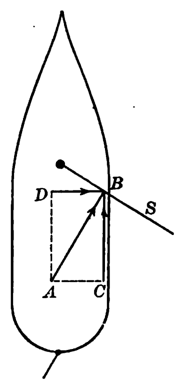


FIGURE 112. — FORCES ON SAILBOAT.

In the case of the sailboat, the sail is set at such an angle that the wind strikes the rear face. In Fig. 112 BS represents the sail, and AB the direction and force of the wind. This force may be resolved into two rectangular components, CB and

DB, of which *CB* represents the intensity of the force that drives the boat forward.

In the case of the aëroplane (Fig. 113), if a large flat surface, placed obliquely to the ground, be moved along rapidly, it will be lifted upward by the vertical component of the reaction of the air against it, equivalent to a wind, just as the kite is lifted. In both the monoplane and the biplane, large bent surfaces attached to a strong light frame are forced through the air by a rapidly rotating propeller driven by a powerful gasoline engine (§ 380). By means of suitable

FIGURE 113. — AËROPLANE.

levers under control of the driver, these planes, or certain auxiliary planes, can be set at an angle to the stream of air against which they are propelled. Then, as with the kite, they rise through the air. Vertical planes are attached to the frame to serve as rudders in steering either to the right or the left.

125. Composition and Resolution of Velocities. — At the Paris exposition in 1900 a continuous moving sidewalk carried visitors around the grounds. A person walking on this platform had a velocity with respect to the ground made up of the velocity of the sidewalk relative to the ground and the velocity of the person relative to the mov-

ing walk. The several velocities entering the result are the *component velocities.* Velocities may be combined and resolved by the same methods as those applying to forces. When several motions are given to a body at the same time, its actual motion is a compromise between them, and the compromise path is the resultant.

The following is an example of the composition of two velocities at right angles: A boat can be rowed in still water at the rate of 5 mi. an hour; what will be its actual velocity if it be rowed 5 mi. an hour across a stream running 3 mi. an hour?

Let AB (Fig. 114) represent in length and direction the velocity of 5 mi. an hour across the stream, and AC, at right angles to AB, the velocity of the current, 3 mi. an hour, both on the same scale. Complete the parallelogram $ABDC$, and draw the diagonal AD through the point A common to the two component velocities. AD represents the actual velocity of the boat; its length on the same scale as that of the other lines is 5.83. The resultant velocity is therefore 5.83 miles an hour in the direction AD.

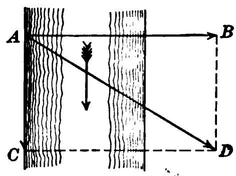


FIGURE 114.—BOAT RUNNING ACROSS STREAM.

When the angle between the components is a right angle, as in the present case, the diagonal AD is the hypotenuse of the right triangle ABD. Its square is therefore the sum of the squares of 5 and 3, or

$$AD = \sqrt{5^2 + 3^2} = 5.83.$$

When the angle at A is not a right angle, the approximate resultant may be found by a graphic process of measurement.

A velocity, like a force, has both direction and magnitude, and a component of it in any given direction may be found in precisely the same way as in the case of a force, (§ 123). The most common case is the resolution into components at right angles to each other. In most cases it suffices to find the component in the direction in which the attention for the time being is directed. The other one at right angles is without effect in this particular direction.

Problems

NOTE. Solve graphically the problems involving forces or velocities at an angle. Consult Appendix I for methods of drawing.

1. Two parallel forces, 40 lb. and 60 lb., act in the same direction on a body with their points of application 30 in. apart. Find the value of the resultant and the distance of its point of application from the greater force.

SUGGESTION. Let x be the distance of the point of application of the resultant from that of the force 60. Then $30-x$ is its distance from the point of application of the force 40. By § 119, $\frac{40}{60}=\frac{x}{30-x}$.

2. A weight of 100 kg. is supported on a joist 5 m. long, the ends of which rest on two parallel walls. If the weight is placed 3 m. from one end of the joist, what part of the weight does each wall sustain?

3. Three parallel forces act simultaneously on a body. Their values are 20, 30, and 40 lb. respectively. The points of application are in a straight line, that of the 30 lb. being 40 in. from that of the 20 lb., and that of the 40 lb. 60 in. from the 30 lb., the order of the forces being that of their magnitudes. Find the resultant and the distance of its point of application from that of the 40 lb. force.

SUGGESTION. Combine the forces 20 lb. and 30 lb.; then combine their resultant with the 40 lb. force.

4. ABC is a straight line; AB is 10 cm. and BC is 15 cm. A force of 300 kg. acts at B at right angles to the line. Replace it by two parallel forces, one at A and the other at C, to produce the same effect as the 300 kg. at B.

5. Two parallel forces of 200 and 300 dynes respectively, have their points of application 40 cm. apart. What third parallel force will produce equilibrium, and where must it be applied so that the three points of application are in the same straight line?

6. Two forces 20 and 30 g. of force, act at an angle of 60°. Find the resultant.

7. Two forces, 40 and 50 lb. of force, act at an angle of 90°. Find the resultant.

8. A parcel was thrown at right angles from a car with a velocity of 10 feet per sec. The car was running 15 mi. per hour. Find the velocity of the parcel with reference to the ground.

9. A canal boat is towed with a force of 100 lb. applied at the end of a rope 250 ft. long. The boat is in the middle of the canal, which is 200 ft. wide. Find what component of the force acts in line with the boat.

10. A ball weighing 30 lb. is suspended by a stout cord. It is pulled aside by a horizontal force of 17.32 lb. of force, and the string then makes an angle of 30° with the vertical. Find the tension in the cord. (Note that in a right triangle with a 30° angle, the side opposite this angle is half the hypotenuse. Could you solve the problem if the horizontal force were not given ?)

III. NEWTON'S LAWS OF MOTION

126. Momentum. — So far we have considered different kinds of motion, or *how* bodies move, without reference to the mass moved, and without considering the relation between force on the one hand and the moving mass and its velocity on the other, or *why* bodies move. Before taking up the laws of motion, which outline the relations between force and motion, it is necessary to define two terms intimately associated with these laws. The first of these is *momentum*. *Momentum is the product of the mass and the linear velocity* of a moving body.

$$\textit{Momentum} = \textit{mass} \times \textit{velocity}, \text{ or } M = mv. \quad \text{(Equation 8)}$$

In the *c.g.s.* system, the unit of momentum is the momentum of a mass of 1 g. moving with a velocity of 1 cm. per second. It has no recognized name. In the English system, the unit of momentum is the momentum of a mass of 1 lb. moving with a velocity of 1 ft. per second.

127. Impulse. — Suppose a ball of 10 g. mass to be fired from a rifle with a velocity of 50,000 cm. per second. Its momentum would be 500,000 units. If a truck weighing 50 kg. moves at the rate of 10 cm. per second, its momentum is also 500,000 units. But the ball has acquired its

momentum in a fraction of a second, while a minute or more may have been spent in giving to the truck the same momentum. In some sense the effort required to set the ball in motion is the same as that required to give the equivalent amount of motion to the truck, because the momenta of the two are equal.

This equality is expressed by saying that the *impulse* is the same in the two cases. Since the effect is doubled if the value of the force is doubled, or if the time during which the force continues to act is doubled, it follows that *impulse is the product of the force and the time it continues to act.* In estimating the effect of a force, the time element and the magnitude of the force are equally important. The term *impulse* takes both into account.

128. Newton's Laws of Motion. — The laws of motion, formulated by Sir Isaac Newton (1642–1727), are to be regarded as physical axioms, incapable of rigorous experimental proof. They must be considered as resting on convictions drawn from observation and experiment in the domain of physics and astronomy. The results derived from their application have so far been found to be invariably true. They form the basis of many of the important principles of mechanics.

129. First Law of Motion. — *Every body continues in its state of rest or of uniform motion in a straight line, unless compelled by applied force to change that state.*

This is known as the *law of inertia* (§ 9), because it asserts that a body persists in a condition of rest or of uniform motion, unless it is compelled to change that state by the action of an external force. It is further true that a body offers resistance to any such change in

proportion to its *mass*. Hence the term *mass* is now often used to denote the measure of a body's inertia (§ 11).

From this law is also derived the Newtonian definition of force, for the law asserts that *force is the sole cause of change of motion.*

130. Second Law of Motion. — *Change of momentum is proportional to the impressed force which produces it, and takes place in the direction in which the force acts.*

The second law points out two things:

First. What the measure is of a force which produces change of motion. Maxwell restated the second law in modern terms as follows: "*The change of momentum of a body is numerically equal to the impulse which produces it, and is in the same direction*"; or in other words,

momentum (mass × velocity) = *impulse* (force × time).

Expressed in symbols, $mv = ft$. . . . (Equation 9)

Hence, $$f = \frac{mv}{t}.$$

The initial velocity of the mass m before the force f acted on it is here assumed to be zero, and v is the velocity attained in t seconds. Then the total momentum imparted in the time t is mv, and therefore $\frac{mv}{t}$ is *the rate of change of momentum. Force is therefore measured by the rate of change of momentum.* Since $\frac{v}{t}$ is the rate of change of velocity, or the acceleration a (see Equation 5), we may write

$$f = ma. \quad . \quad . \quad . \quad \text{(Equation 10)}$$

We see from this that *force may also be measured by the product of the mass moved and the acceleration imparted to it.* Therefore when the mass m is unity, the force is numerically equal to the acceleration it produces. Hence the definition of the *dyne* (§ 114).

Second. This law also points out that *the change of momentum is always in the direction in which the force acts.* Hence, when two or more forces act together, each produces its change of momentum independently of the others and in its own direction. This principle lies at the foundation of the method of finding the resultant effect of two forces acting on a body in different directions (§ 118).

On a horizontal shelf about two meters above the floor are placed two marbles, one on each side of a straight spring fixed vertically over a hole in the shelf. One marble rests on the shelf and the other is held over the hole between the spring and a block fixed to the shelf (Fig. 115). When the hammer falls and strikes the spring, it projects the one marble horizontally and lets the other one fall vertically. The two reach the floor at the same instant. Both marbles have the same vertical acceleration.

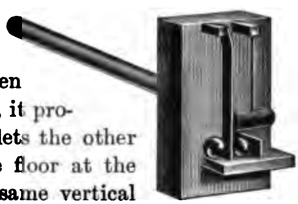


FIGURE 115. — ILLUSTRATING SECOND LAW OF MOTION.

131. Third Law of Motion. — *To every action there is always an equal and contrary reaction; or the mutual actions of two bodies are always equal and oppositely directed.*

The essence of this law is that all action between two bodies is *mutual.* Such action is known as a *stress* and a stress is always a two-sided phenomenon, including both *action* and *reaction.* The third law teaches that these two aspects of a stress are always equal and in opposite directions. The stress in a stretched elastic cord pulls the two

bodies to which it is attached equally in opposite directions; the stress in a compressed rubber buffer or spring exerts an equal push both ways; the former is called a *tension* and the latter a *pressure.*

ILLUSTRATIONS. The tension in a rope supporting a weight is a stress tending to part it by pulling adjacent portions in opposite directions. The same is obviously true if two men pull at the ends of

AËROPLANE IN FLIGHT OVER A FIELD IN FRANCE.

The propeller is revolving so rapidly that it can hardly be seen.

the rope. An ocean steamship is pushed along by the reaction of the water against the blades of the propeller. The same is true of an aëroplane, only in this case the reaction against the blades is by the air, and the blades are longer and revolve much faster than in water in order to move enough air to furnish the necessary reaction. When a man jumps from a rowboat to the shore, he thrusts the boat backwards. An athlete would not make a record standing jump from a feather bed or a spring board. When a ball is shot from a gun, the gun recoils or "kicks." All attraction, such as that between a magnet and a piece of iron, is a stress, the magnet attracting the iron and the iron the magnet with the same force.

Practical use is made of reaction to turn the oscillating electric fan from side to side so as to blow the air in different directions. A rectangular sheet of brass is bent lengthwise at right angles and is pivoted so as to turn 90° about a vertical axis (Fig. 116). When one half of this bent sheet is exposed to the air current, the reaction sustained by the blades of the fan on this side is in part balanced by the reaction of the bent sheet; but on the opposite half of the fan the reaction of the blades is not balanced. Hence the whole fan turns about a vertical axis on the standard until a lever touches a stop and shifts the bent strip so as to expose the other half of it to the air current from the opposite half of the fan. The fan then reverses its slow motion and turns to the other side.

FIGURE 116. — OSCILLATING FAN.

Since force is measured by the rate at which momentum changes, the third law of motion is equivalent to the following:

In every action between two bodies, the momentum gained by the one is equal to that lost by the other, or the momenta in opposite directions are the same.

Problems

1. What relative velocities will equal *impulses* impart to the masses 5 lb. and 8 lb. respectively?

2. A body of 50 g. is moving with a velocity of 20 cm. per second. What is its momentum?

3. Find the ratio of the momentum of a body whose mass is 10 lb., moving with a uniform velocity of 50 ft. per second to that of a body whose mass is 25 lb. and whose velocity is 20 ft. per second.

4. Two bodies have equal momenta. One has a mass of 2 lb. and a velocity of 1500 ft. per second, the other a mass of 100 lb. What is the velocity of the second body?

5. What is the velocity of recoil of a gun whose mass is 5 kg., the mass of the ball being 25 g. and its velocity 600 m. per second?

6. An unbalanced force of 500 dynes acts for 5 sec. on a mass of 50 g. What will be the velocity produced?

7. A force of 980 dynes acts on a mass of 1 g. What is the acceleration? How far will the body go in 10 sec.?

8. A force of 400 dynes acts on a body for 10 sec. What will be the momentum at the end of this period?

9. A body is acted on by a force of 100 dynes for 20 sec. and acquires a velocity of 200 cm. per second. What is its mass?

10. A force of 10 g. acts for 5 sec. on a body whose mass is 15 g. What velocity is imparted?

11. What force in grams of force can impart to a mass of 50 g. an acceleration of 980 cm.-per-second per second?

12. A force of 50 g. acts for 5 sec. on a mass of 50 g. How far will the body have gone in that time, starting from rest?

IV. GRAVITATION

132. Weight. — *The attraction of the earth for all bodies is called gravity.* The *weight* of a body is the measure of this attraction. It is a pull on the body and therefore a force. It makes a body fall with uniform acceleration called the *acceleration of gravity* and denoted by g. If we represent the weight of a body by w and its mass by m, by Equation 10, $w = mg$. From this it appears that *the weight of a body is proportional to its mass*, and that *the ratio of the weights of two bodies at any place is the same as that of their masses.* Hence, in the process of weighing with a beam balance, the mass of the body weighed is compared with that of a standard mass. When a beam balance shows equality of weights, it shows also equality of masses.

133. Direction of Gravity. — The direction in which the force of gravity acts at any point is very nearly toward the earth's center. It may be determined by suspending a weight by a cord passing through the point. The cord

is called a *plumb line* (Fig. 117), and its direction is a *vertical line.* A plane or line perpendicular to a plumb line is said to be *horizontal.* Vertical lines drawn through neighboring points may be considered parallel without sensible error.

FIGURE 117. — PLUMB LINE.

134. Center of Gravity. — In Physics a body is thought of as composed of an indefinitely large number of parts, each of which is acted on by gravity. For bodies of ordinary size, these forces of gravity are parallel and proportional to the masses of the several small parts. *The point of application of their resultant is the center of gravity of the body.*

If the body is uniform throughout, the position of its center of gravity depends on its geometrical figure only. Thus, the center of gravity (1) of a straight rod is its middle point; (2) of a circle or ring, its center; (3) of a sphere or a spherical shell, its center; (4) of a parallelogram, the intersection of its diagonals; (5) of a cylinder or a cylindrical pipe, the middle point of its axis.

It is necessary to guard against the idea that the force of gravity on a body acts at its center of gravity. Gravity acts on all the particles composing the body, but its effect is generally the same as if the resultant, that is, the weight of the body, acted at its center of gravity. It will be seen from the examples of the ring and the cylindrical pipe that the center of gravity may lie entirely outside the body.

135. Law of Universal Gravitation. — It had occurred to Galileo and the other early philosophers that the attraction of gravity extends beyond the earth's surface, but it

remained for Sir Isaac Newton to discover the law of universal gravitation. He derived this great generalization from a study of the planetary motions discovered by Kepler. The law may be expressed as follows:

Every portion of matter in the universe attracts every other portion, and the stress between them is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers of mass.

For spherical bodies, like the sun, the earth, and the planets, the attraction of gravitation is the same as if all the matter in them were concentrated at their centers; hence, in applying to them the law of gravitation, the distance between them is the distance between their centers. Calculations made to find the centripetal acceleration of the moon in its orbit show that it is attracted to the earth with a force which follows the law of universal gravitation.

The law of universal gravitation does not refer in any way to *weight* but to *mass*. It would be entirely meaningless to speak of the *weight* of the earth, or of the moon, or of the sun, but their *masses* are very definite quantities, the ratios of which are well known in astronomy. Thus the mass of the earth is about 80 times that of the moon, and the mass of the sun is about 332,000 times that of the earth. The weight of a pound mass at the distance of the moon is only $\frac{1}{3600}$ the weight of a pound mass at the surface of the earth.

136. Variation of Weight. — Since the earth is not a sphere but is flattened at the poles, it follows from the law of gravitation that the acceleration of gravity, and the weight of any body, increase in going from the equator toward either pole. If the earth were a uniform sphere and stationary, the value of g would be the same

Sir Isaac Newton (1642–1727) is celebrated for his discoveries in mathematics and physics. He was a Fellow of Trinity College, Cambridge. He discovered the binomial theorem in algebra and laid the foundation of the calculus. His greatest work is the *Principia*, a treatise on motion and the laws governing it. His greatest discoveries are the laws of gravitation and the composition of white light.

From Kepler's laws of the planetary orbits Newton proved that the attraction of the sun on the planets varies inversely as the squares of their distances.

He was also distinguished in public life. He sat in Parliament for the University of Cambridge, was at one time Master of the Mint, and the reformation of the English coinage was largely his work.

all over its surface. But the value of g varies from point to point on the earth's surface, even at sea level, both because the earth is not a sphere and because it rotates on its axis. The centripetal acceleration of a point at the equator, owing to the earth's rotation on its axis, is $\frac{1}{289}$ the acceleration of gravity g. Since 289 is the square of 17, and the centripetal acceleration varies as the square of the velocity (§ 110), it follows that if the earth were to rotate in one seventeenth of a day, that is, 17 times as fast as it now rotates, the apparent value of g at the equator would become zero, and bodies there would lose all their weight.

The value of g at the equator is 978.1 and at the poles 983.1, both in centimeters-per-second per second. At New York it is 980.15 centimeters-per-second per second, or 32.16 feet-per-second per second.

137. Equilibrium under Gravity. — When a body rests on a horizontal plane, its weight is equal and opposite to the reaction of the plane. The vertical line through its center of gravity must therefore fall within its base of support. If this vertical line falls outside the base, the weight of the body and the reaction of the plane form a couple (§ 121), and the body overturns.

The three kinds of equilibrium are (1) *stable*, for any displacement which causes the center of gravity to rise; (2) *unstable*, for any displacement which causes the center of gravity to fall; (3) *neutral*, for any displacement which does not change the height of the center of gravity.

Fill a round-bottomed Florence flask one quarter full of shot and cover them with melted paraffin to keep them in place (Fig. 118). Tip the flask over; after a few oscillations it will return to an upright position. Repeat the experiment with a similar empty flask; it will not stand up, but will rest in any position on its side and with

the top on the table. The loaded flask cannot be tilted over without raising its center of gravity; in a vertical position it is therefore stable and when tipped over, unstable, for it returns to a vertical position. For the empty flask, its center of gravity is lower when it lies on its side than when it is erect. Rolling it around does not change the height of its center of gravity and its equilibrium is thus neutral.

FIGURE 118. — STABILITY OF FLASKS.

The three funnels of Fig. 119 illustrate the three kinds of equilibrium on a plane.

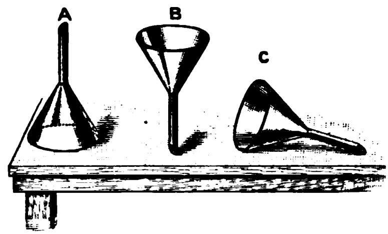


FIGURE 119. — STABILITY OF FUNNELS.

A rocking horse, a rocking chair, and a half sphere resting on its convex side are examples of stable equilibrium. An egg lying on its side is in neutral equilibrium for rolling and stable equilibrium for rocking; it is unstable on either end. A lead pencil supported on its point is in unstable equilibrium. Any such body may become stable by attaching weights to it in such a manner as to lower the center of gravity below the supporting point (Fig. 120).

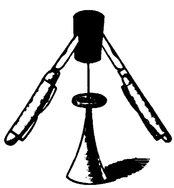


FIGURE 120. — CENTER OF GRAVITY BELOW SUPPORT.

138. Stability. — *Stability is the state of being firm or stable.* The higher the center of gravity of a body must be lifted to put the body in unstable equilibrium or to overturn it, the greater is its stability. This condition is met by a relatively large base and a low center of gravity. A pyramid is a very stable form. On account of the large area lying within the four feet of a quadruped, its stability is greater than that of a biped. A child is therefore able

to creep "on all fours" before it learns to maintain stable equilibrium in walking. A boy on stilts has smaller stability than on his feet because his support is smaller and his center of gravity higher.

Stability may be well illustrated by means of a brick. It has greater stability when lying on its narrow side (2″ × 8″) than when standing on end; and on its broad side (4″ × 8″) its stability is still greater. Let Fig. 121 represent a brick lying on its narrow side in *A* and standing on end in *B*. In both cases to overturn it its center of gravity *c* is lifted to the same height, but the vertical distance *bd* through which the center of gravity must be lifted is greater in *A* than in *B*.

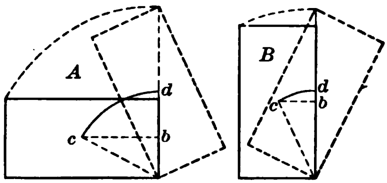


FIGURE 121. — DEGREES OF STABILITY.

A tall chimney or tower has no great stability because its base is relatively small and its center of gravity high. A high brick wall is able to support a great crushing weight, but its stability is small unless it is held by lateral walls and floor beams.

Questions and Problems

1. If one jumps off the top of an empty barrel standing on end, why is one likely to get a fall?

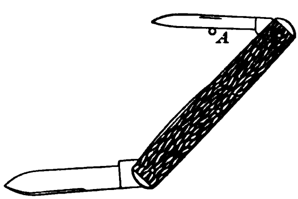


FIGURE 122.

2. Where is the center of gravity of a knife supported as in Fig. 122?

3. Given a triangle cut from a uniform sheet of cardboard or thin wood. Describe two methods of finding its center of gravity. How can you tell when the right center has been found?

4. Represent a hill by the hypotenuse of a right triangle, and a ball on the hill by a circle, the circumference of the circle just touching the hypotenuse of the triangle. How would you represent the weight of the ball? By resolving this force into two components, find the force that rolls

the ball down the hill and the force with which the ball presses against it.

5. Which is less likely to "turn turtle" in rounding a sharp curve, an underslung or an overslung automobile? Why?

6. A body weighing 150 lb. on a spring balance on the earth would weigh how much on the moon, the radius of the moon being $\frac{1}{4}$ that of the earth and its mass $\frac{1}{80}$?

FIGURE 123. — CATHEDRAL OF PISA AND LEANING TOWER.

7. If the acceleration of gravity is 32.2 ft.-per-second per second on the earth, what must it be on the sun, the radius of the sun being taken as 110 times that of the earth and its mass as 330,000 times?

8. With what force will a man weighing 160 lb. press on the floor of an elevator when it starts with an acceleration of 4 ft.-per-second per second, — first going up, and then going down?

V. FALLING BODIES

139. Rate at which Different Bodies Fall. — It is a familiar fact that heavy bodies, such as a stone or a piece of iron,

fall much faster than such light bodies as feathers, bits of paper, and snow crystals. Before the time of Galileo it was supposed that different bodies fall with velocities proportional to their weights. This erroneous notion was corrected by Galileo by means of his famous experiment of dropping various bodies from the top of the leaning tower of Pisa (Fig. 123) in the presence of professors and students of the university in that city. He showed that bodies of different materials fell from the top of the tower to the ground, a height of 180 feet, in practically the same time; also that light bodies, such as paper, fell with velocities approaching more and more nearly those of heavy bodies the more compactly they were rolled together in a ball. The slight differences in the velocities observed he rightly ascribed to the resistance of the air, which is relatively greater for light bodies than for heavy compact ones. This inference Galileo could not completely verify because the air pump had not yet been invented.

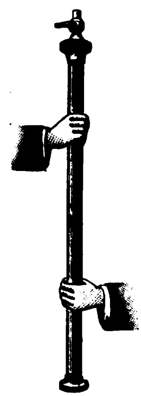


FIGURE 124. — GUINEA AND FEATHER TUBE.

140. Resistance of the Air. — Place a small coin and a feather, or a shot and a bit of tissue paper, in a glass tube from 4 to 6 feet long. It is closed at one end and fitted with a stopcock at the other (Fig. 124). Hold the tube in a vertical position and suddenly invert it; the coin or the shot will fall to the bottom first. Now exhaust the air as perfectly as possible; again invert the tube quickly; the lighter body will now fall as fast as the heavier one. This experiment is known as the "Guinea and Feather Tube." It demonstrates that if the resistance of the air were wholly removed, all bodies at the same place would fall with the same acceleration.

An interesting modification of the experiment is the following: Cut a round piece of paper slightly smaller than a cent and drop the cent and the paper side by side; the cent will reach the floor

first. Then lay the paper *on the cent* and drop them in that position; the paper will now fall as fast as the cent. Explain.

The friction of the air against the surface of bodies moving through it limits their velocity. A cloud floats, not because it is lighter than the atmosphere, for it is actually heavier, but because the surface friction is so large in comparison with the weight of the minute drops of water, that the limiting velocity of fall is very small.

When a stream of water flows over a high precipice, it is broken into fine spray and falls slowly. At the Yosemite Fall (Fig. 125) a large stream is broken by the resistance of the air until at the bottom of its 1400 foot drop it becomes fine spray.

141. Laws of Falling Bodies. — Galileo verified the following laws of falling bodies:

I. *The velocity attained by a falling body is proportional to the time of falling.*

II. *The distance fallen is proportional to the square of the time of descent.*

III. *The acceleration is twice the distance a body falls in the first second.*

These laws will be recognized as identical with those derived for uniformly accelerated motion, §§ 106 and 107. If the inclined plane in Galileo's experiment be tilted up steeper, the effect will be to increase the acceleration down the plane; and if the board be raised to a vertical position, the ball will fall freely under gravity and the acceleration will become g (§ 136).

Since the acceleration g is sensibly constant for small distances above the earth's surface, the equations already obtained for uniformly accelerated motion may be applied directly to falling bodies, by substituting g for a in Equations 5 and 6. Thus we have

$$v = gt, \quad . \quad . \quad . \quad \text{(Equation 11)}$$

and

$$s = \tfrac{1}{2} gt^2. \quad . \quad . \quad \text{(Equation 12)}$$

FIGURE 125. — YOSEMITE FALL.

If in Equation 12 t is one second, $s = \frac{1}{2}g$; or the distance a body falls from rest in the first second is half the acceleration of gravity. A body falls 490 cm. or 16.08 ft. the first second; and the velocity attained is 980 cm. or 32.16 ft. per second.

142. Projection Upward. — When a body is thrown vertically upward, the acceleration is negative, and it loses each second g units of velocity (980 cm. or 32.16 ft.). Hence, the time of ascent to the highest point is the time taken to bring the body to rest. If the velocity lost is g units a second, the time required to lose v units of velocity will be the quotient of v by g, or

$$\textit{time of ascent} = \frac{\textit{velocity of projection upward}}{\textit{acceleration of gravity}}.$$

In symbols $$t = \frac{v}{g} \quad . \quad . \quad . \quad . \quad \text{(Equation 13)}$$

For example, if the velocity of projection upward were 1470 cm. per second, the time of ascent, neglecting the frictional resistance of the air, would be $\frac{1470}{980}$, or 1.5 seconds. This is the same as the time of descent again to the starting point; hence, *the body will return to the starting point with a velocity equal to the velocity of projection but in the opposite direction.* In this discussion of projection upward, the resistance of the air is neglected.

Problems

Unless otherwise stated in the problem, g is to be taken as 980 cm.- or 32 ft.-per-second per second.

1. The tower of Pisa is 180 ft. high. In what time would a ball dropped from the top reach the ground? With what velocity would it strike?

2. From what height must a ball fall to acquire a velocity of 1 km. per second?

3. With what velocity in a vertical direction must a shell be fired just to reach an aëroplane flying at an elevation of one mile?

4. A ball is fired vertically with an initial velocity of 500 m. per second. Neglecting the resistance of the air, to what height will it rise, and in what time will it return to the earth?

5. An aëroplane flying westward with a velocity of 60 mi. per hour and at an elevation of one mile, dropped a bomb while vertically over a cathedral. How far from the cathedral did the bomb strike the ground and in which direction?

6. A ball fired horizontally reaches the ground in 4 sec. What was the height of the point from which it was fired?

7. A cannon ball is fired horizontally from a fort at an elevation of 122.5 m. above the neighboring sea. How many seconds before it will strike the water?

8. The Washington monument is 555 ft. high. Two balls are dropped from its top one second apart. How far apart will the balls be when the first one strikes the ground?

9. An iron ball was dropped from an aëroplane moving eastward at the rate of 45 mi. per hour. It reached the ground 528 ft. east of the vertical line through the point from which it was dropped. What was the elevation of the aëroplane?

10. A body slides without friction down an inclined plane 300 cm. long and 24.5 cm. high. If it moves 40 cm. during the first second, what is the computed value of g?

VI. CENTRIPETAL AND CENTRIFUGAL FORCE

143. Definition of Centripetal and Centrifugal Force. — Attach a ball to a cord and whirl it around by the hand. The ball pulls on the cord, the pull increasing with the velocity of the ball. If the ball is replaced by a heavier one, with the same velocity the pull is greater. If a longer cord is used, the pull is less for the same velocity in the circle.

The constant pull which deflects the body from a rectilinear path and compels it to move in a curvilinear one is the centripetal force.

The resistance which a body offers on account of its inertia, to deflection from a straight line is the centrifugal force. When the motion is uniform and circular, the force is at right angles to the path of the body around the circle and constant.

These two forces are the two aspects of the stress in the cord (third law of motion), the action of the hand on the ball, and the reaction of the ball on the hand.

144. Value of Either Force. — The centripetal acceleration for uniform circular motion (§ 110) is $a = \frac{v^2}{r}$, where v is the uniform velocity in the circle, and r is the radius. Further, in § 130 the relation between force and acceleration was found to be as follows: force equals the product of the mass and the acceleration imparted to it by the force. Hence we have

$$\textit{centripetal force} = \textit{mass} \times \textit{centripetal acceleration},$$

or

$$f = \frac{mv^2}{r}. \quad . \quad . \quad . \quad \text{(Equation 14)}$$

This relation gives the value of either the centripetal or the equal centrifugal force in the absolute system of measurement, because it is derived from the laws of motion and is independent of gravity. In the metric system m must be in grams, v in centimeters per second, and r in centimeters; f is then in dynes. To obtain f in grams of force, divide by 980 (§ 115). In the English system, m must be in pounds, v in feet per second, and r in feet; dividing by 32.2, the result will be in pounds of force.

For example: If a mass of 200 g. is attached to a cord 1 m. long and is made to revolve with a velocity of 140 cm. per second, the tension in the cord is $\frac{200 \times 140^2}{100} = 39{,}200$ dynes $= \frac{39200}{980} = 40$ grams of force.

Again if a body having a mass of 10 lb. 1 oz. move in a circle of 5 ft. radius with a velocity of 20 ft. per second, then the centripetal force is $f = \frac{10\frac{1}{16} \times 20^2}{5 \times 32.2} = 25$ pounds of force.

145. Illustrations of Centrifugal Force. — Water adhering to the surface of a grindstone leaves the stone as soon as the centrifugal force, increasing with the velocity, is greater than the adhesion of the water to the stone. Grindstones and flywheels occasionally burst when run at too high a speed, the latter when the engine runs away after a heavy load is suddenly thrown off. When the centripetal force ceases to deflect the body from the tangent to the circle, the body flies off along the tangent line. A stone is thrown by whirling it in a sling and releasing one of the strings.

A carriage or an automobile rounding a curve at high speed is subject to strong centrifugal forces, which act through the tires. The centripetal force consists solely of the friction between the tires and the ground. If the friction is insufficient, "skidding" takes place.

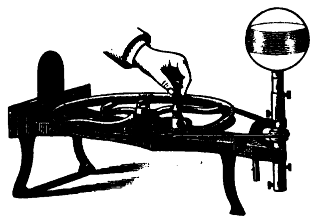


FIGURE 126. — WHIRLING LIQUIDS.

When a spherical vessel containing some mercury and water is rapidly whirled on its axis (Fig. 126), both the mercury and the water rise and form separate bands as far as possible from the axis of rotation, the mercury outside.

Centrifugal machines are used in sugar refineries to separate sugar crystals from the sirup, and in dyeworks and laundries to dry yarn and wet clothes by whirling them rapidly in a large cylinder with openings in the side. Honey is extracted from the comb in a similar way. When light and heavy particles are whirled together, the heavier ones tend toward the outside. New milk is an emulsion of fat and a liquid, and the fat globules are lighter than the liquid of the emulsion. Hence, when fresh milk is whirled in a dairy separator, the cream and the milk form distinct layers and collect in separate chambers.

VII. THE PENDULUM

146. Simple Pendulum. — Any body suspended so as to swing about a horizontal axis is a *pendulum*. A *simple pendulum* is an ideal one. It may be defined as a material particle without size suspended by a cord without weight. A small lead ball suspended by a long thread without sensible mass represents very nearly a simple pendulum. When at rest the thread hangs vertically like a plumb line; but if the ball be drawn aside and released, it will *oscillate* about its position of rest. Its oscillations become gradually smaller; but if the arc described be small, the period of its swing will remain unchanged.

This feature of pendular motion first attracted the attention of Galileo while watching the slow oscillations of a "lamp" or bronze chandelier, suspended by a long rope from the roof of the cathedral in Pisa. Galileo noticed the even time of the oscillations as the path of the swinging chandelier became shorter and shorter. Such a motion, which repeats itself over and over in equal time intervals, is said to be *periodic*.

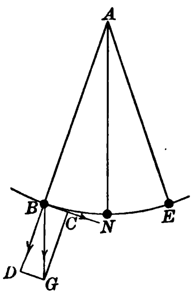


FIGURE 127. — FORCES ACTING ON A PENDULUM.

147. The Motion of a Pendulum. — AN in Fig. 127 is a nearly simple pendulum with the ball at N. When the ball is drawn aside to the position B, its weight, represented by BG, may be resolved into two components, BD in the direction of the thread, and BC at right angles to it and tangent to the arc BNE. The latter is the force which produces motion of the ball toward N.

As the ball moves from B toward N the component BC becomes smaller and smaller and vanishes at N, where the whole weight of the ball is in the direction of the thread. In falling from B to N, the ball moves in the arc of a circle under the influence of a force which is greatest at B and becomes zero at N. The motion is therefore

INTERIOR OF PISA CATHEDRAL.

The bronze chandelier which Galileo observed hangs just in front of the altar.

accelerated all the way from B to N, but not uniformly. The velocity increases continuously from B to N, but at a decreasing rate.

The ball passes N with its greatest velocity and continues on toward E. From N to E the component of the weight along the tangent which is always directed toward N, opposes the motion and brings the pendulum to rest at E. It then retraces its path and continues to oscillate with a *periodic* and *pendular motion.*

148. Definition of Terms. — The *center of suspension* is the point or axis about which the pendulum swings. A *single vibration* is the motion comprised between two successive passages of the pendulum through the lowest point of its path, as the motion from N to B (Fig. 128) and back to N again. A *complete* or *double vibration* is the motion between two successive passages of the pendulum through the same point and going in the same direction. A complete vibration is double that of a single one. The *period of vibration* is the time consumed in making a complete or double vibration. The *amplitude* is the arc BN or the angle BAN.

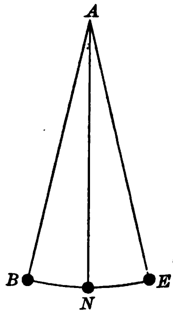


FIGURE 128. — SIMPLE PENDULUM.

149. Laws of the Pendulum. — The following are the laws of a simple pendulum which are independent of both the material and the weight:

I. *For small amplitudes, the period of vibration is independent of the amplitude.*

II. *The period of vibration is proportional to the square root of the length of the pendulum.*

III. *The period of vibration is inversely proportional to the square root of the acceleration of gravity.*

One of the earliest and most important discoveries by Galileo was that of the experimental laws of the motion of

a pendulum, made when he was about twenty years of age. This was long before their theoretical investigation.

If the period of a single vibration of a simple pendulum is denoted by t, the length by l, and the acceleration of gravity by g, it can be shown that

$$t = \pi\sqrt{\frac{l}{g}}. \quad . \quad . \quad . \quad \text{(Equation 15)}$$

To illustrate Law I. It is only necessary to count the vibrations of a pendulum which take place in some convenient time with different amplitudes. Their number will be found to be the same. This result will hold even when the amplitudes are so small that the vibrations can only be observed with a telescope.

To illustrate Law II. Mount three pendulums (Fig. 129), making the lengths 1 m., $\frac{1}{4}$ m., and $\frac{1}{9}$ m. respectively. Observe the period of a single vibration for each. They will be 1 sec., $\frac{1}{2}$ sec., and $\frac{1}{3}$ sec. nearly, or in periods proportional to the square root of the lengths.

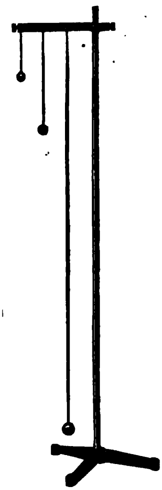


FIGURE 129. — PENDULUMS OF DIFFERENT LENGTHS.

In accordance with Law III a pendulum oscillates more slowly on the top of a high mountain than at sea level, and more slowly at the equator than at the poles. Place a strong magnet just under the bob of the longest pendulum, which must be iron. It will then be found to vibrate in a slightly shorter period than before. The downward magnetic pull on the bob is equivalent to an increased value of g.

150. Center of Oscillation. — Insert a small staple in one end of a meter stick, and suspend it so as to swing as a pendulum about a horizontal axis through the staple (Fig. 130). With a ball and a thread make a simple pendulum that will vibrate in the same period as the meter stick. Beginning at the staple, lay off on the meter stick the length of this

FIGURE 130. — CENTER OF OSCILLATION.

pendulum. It will extend two thirds of a meter down. Bore a hole through the meter stick at the point thus found, and suspend it as a pendulum by means of a pin through this hole. Its period of vibration will be the same as before.

The bar is a compound pendulum, and the new axis of vibration is called the *center of oscillation.* The distance between the center of suspension and the center of oscillation is the length of the equivalent simple pendulum that vibrates in the same period as the compound pendulum. The centers of suspension and of oscillation are interchangeable without change of period.

151. Center of Percussion. — Suspend the meter bar by the staple at the end and strike it with a soft mallet at the center of oscillation. It will be set swinging smoothly and without perceptible jar.

Hold a thin strip of wood a meter long and four or five centimeters wide by the thumb and forefinger near one end. Strike the flat side with a soft mallet at different points. A point may be found where the blow will not throw the wood strip into shivers, but will only set it swinging like a pendulum.

The center of oscillation is also called the *center of percussion;* if the suspended body be struck at this point at right angles to the axis of suspension, it will be set swinging without jar. A baseball club or a cricket bat has a center of percussion, and it should strike the ball at this point to avoid breaking the bat and "stinging" the hands.

152. Application of the Pendulum. — Galileo's discovery suggested the use of the pendulum as a timekeeper. In the common clock the oscillations of the pendulum regulate the motion of the hands. The wheels are kept in motion by a weight or a spring, and the regulation is effected by means of the escapement (Fig. 131). The pendulum rod, passing between the prongs of a fork *a*, communicates its motion to an axis carrying the escapement, which ter-

minates in two pallets *n* and *m*. These pallets engage alternately with the teeth of the escapement wheel *R*, one tooth of the wheel escaping from a pallet every double vibration of the pendulum. The escapement wheel is a part of the train of the clock; and as the pendulum controls the escapement, it also controls the motion of the hands.

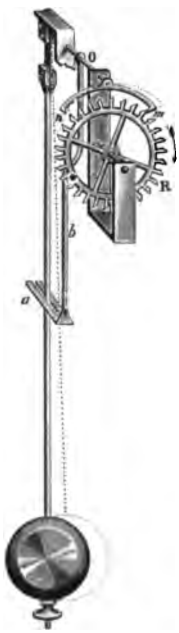


FIGURE 131. — ESCAPEMENT.

153. Seconds Pendulum. — A seconds pendulum is one making a single vibration in a second. Its length in New York is 99.31 cm. This is the length of the equivalent simple pendulum vibrating seconds. The value of gravity g increases from the equator to the poles, and the length of the seconds pendulum increases in the same proportion.

Questions and Problems

1. Why can a heavy shot be thrown much farther by swinging it from the end of a short wire or cord than by hurling it from the shoulder as in "putting the shot"?

2. Why is the outer rail on a railway curve elevated above the inner one?

3. A ball weighing 10 lb. is attached to a cord 2 ft. long and is whirled about the hand at the rate of ten revolutions in three seconds. What is the tension in the cord?

4. A ball swings as a conical pendulum; its mass is 2 kg., its distance from the center of its circular path is 30 cm., and it makes ten revolutions in 35 seconds. What horizontal force in grams would be necessary to hold the ball at any point in its path if it were not revolving?

5. Find the period of vibration of a pendulum 70 cm. long, the value of g being 980 cm.-per-second per second.

6. Calculate the length of a seconds pendulum at a place where the value of g is 980 cm.-per-second per second.

7. At a place where g is 32 ft.-per-second per second what is the length of a pendulum that vibrates in $\frac{1}{2}$ sec.?

8. What would be the acceleration of gravity if a pendulum one meter long had a period of vibration of one second?

9. If a simple pendulum 90 cm. long makes 64 single vibrations per minute, what is the value of g?

10. Two balls of the same diameter but of different materials and masses are suspended by threads of the same length and of negligible mass. If made to vibrate as pendulums, will their periods of vibration differ and why?

CHAPTER VI

MECHANICAL WORK

I. WORK AND ENERGY

154. Work. — A man does work in climbing a hill by lifting himself against the pull of gravity; a horse does work in drawing a wagon up an inclined roadway; a locomotive does work in hauling a train on the level against frictional resistances; gravity does work against the inertia of the mass when it causes the weight of a pile

THE LARGEST AND MOST POWERFUL LOCOMOTIVE IN THE WORLD.

driver to descend with increasing velocity; steam does work on the piston of a steam engine and moves it by pressure against a resistance; the electric current does work by means of a motor when it drives an air compressor on an electric car and forces air into a compression tank.

Mechanical work means the overcoming of resistance. Unless there is a component of motion in the direction in which the force acts in overcoming the resistance, no work in a physical sense is done. The columns in a modern steel building do no work, though they sustain great

weight; the pillars supporting a pediment over a portico do no work; a person holding a weight suffers fatigue, but does no work in the sense in which this word is used in physics, where it is employed to describe the *result accomplished* and not the *effort* made.

155. Measure of Mechanical Work. — Mechanical work is measured by the product of the force and the displacement of its point of application in the direction in which the force acts, or

$$work = force \times displacement.$$

In symbols

$$w = f \times s. \quad . \quad . \quad . \quad \text{(Equation 16)}$$

Since force is equal to the product of mass and acceleration (§ 130),

$$w = ma \times s. \quad . \quad . \quad . \quad \text{(Equation 17)}$$

156. Units of Work. — Before use can be made of these expressions for work, it is necessary to define the units employed in measuring work. Three or four such units are in common use:

1. The *foot pound* (ft. lb.), or the work done by a pound of force working through a space of one foot. If a pound weight is lifted a foot high, or if a body is moved a distance of one foot by a force of one pound, a foot pound of work is done. This unit is in common use among English-speaking engineers. It is open to the objection that it is variable, since a pound of force varies with the latitude and with the elevation above sea level.

2. The *kilogram meter* (kg. m.), or the work done by a kilogram of force working through a space of one meter. It is the gravitational unit of work in the metric system, and varies in the same manner as the foot pound. The *gram-centimeter* is also used as a smaller gravitational

unit of work. The kilogram meter is equal to 100,000 gram-centimeters.

3. The *erg*,[1] or the work done by a dyne working through a distance of one centimeter. The erg is the absolute unit in the *c. g. s.* system and is invariable.

Since a gram of force is equal to 980 dynes (§ 115), if a gram mass be lifted vertically one centimeter, the work done against gravity is 980 ergs. Hence one kilogram meter is equal to $980 \times 1000 \times 100 = 98{,}000{,}000$ ergs.

The mass of a "nickel" is 5 g. The work done in lifting it through a vertical distance of 5 m. is the continued product of 5, 500, and 980, or 2,450,000 ergs. The erg is therefore a very small unit and not suitable for measuring large quantities of work. For such purposes it is more convenient to use a multiple of the erg, called the *joule*.[2] Its value is

$$1\ joule = 10^7\ ergs = 10{,}000{,}000\ ergs.$$

Expressed in this larger unit, the work done in lifting the "nickel" is 0.245 joule.[3]

157. Power. — While it takes time to do work, it is plain that time is not an element in the *amount of work done*. To illustrate: Suppose a ton of marble is lifted by a steam engine out of a marble quarry 300 ft. deep. The work is done by means of a wire rope, which the engine winds on a drum. If now the drum be replaced by another of twice the diameter, and running at the same rate of rotation, the ton of marble will be lifted in half the time; but the total work done against gravity remains the same, namely, 600,000 ft. lb.

In an important sense the engine as an agent for doing work is twice as effective in the second instance as in the

[1] The erg is from the Greek word meaning work.

[2] From the noted English investigator Joule.

[3] The joule is equal to about ¾ of a foot pound.

first. Time is an essential element in comparing the capacities of agents to do work. Such a comparison is made by measuring the *power* of an agent. Power tells us not *how much* work is done, but *how fast* it is done.

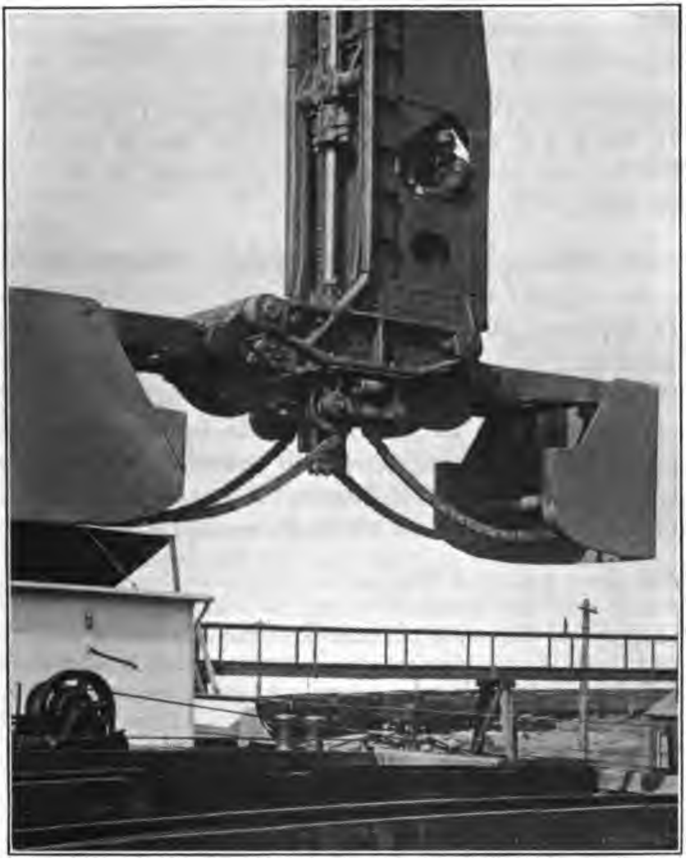
A MARBLE QUARRY.

Power is the time rate of doing work, or

$$power = \frac{work}{time} = \frac{f \times s}{t}. \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \text{(Equation 18)}$$

This expression may be used directly to measure power, due regard being paid to the units employed. The result will be in foot pounds per second, kilogram meters per second, gram-centimeters per second, or ergs per second, according to the consistent units used.

The units of power universally used by engineers are



GIANT ORE CRANE.

When these jaws close, as shown in the picture on page 153, the bucket holds 12 tons of iron ore.

either the *horse power* or the *watt* and its multiple the *kilowatt*.

The *horse power* (H.P.) is the rate of working equal to 33,000 ft. lb. per minute, or to 550 ft. lb. per second.

Hence
$$H.P. = \frac{f \times s}{550 \times t}. \quad . \quad . \quad . \quad \text{(Equation 19)}$$

in which f is in pounds of force, s in feet, and t in seconds.

In the *c. g. s.* system the *watt*[1] is the rate of working equal to one joule per second. A *kilowatt* (K.W.) is 1000 watts.

Hence
$$watts = \frac{f \times s}{t \times 10^7}; \ K.W. = \frac{f \times s}{t \times 10^{10}}. \quad \text{(Equation 20)}$$

In Equation 20 f is in dynes, s in centimeters, and t in seconds.

One horse power equals 746 watts, or 0.746 kilowatt (nearly $\frac{3}{4}$ K.W.). To convert kilowatts into horse powers approximately, add one third; to convert horse powers into kilowatts, subtract one fourth. For example, 60 K.W. are equal to 80 H.P., and 100 H.P. are equal to 75 K.W.

The power capacity of direct current dynamo electric generators is now universally expressed in kilowatts; the steam engines and water turbines used to drive these generators are commonly rated in the same unit of power; so, too, the capacity of electric motors is more often given in kilowatts than in horse powers. A *kilowatt hour* means power at the rate of a kilowatt expended for one hour. Thus, 20 kilowatt hours mean 20 K.W. for one hour, or 5 K.W. for four hours, etc.

158. Energy. — Experience teaches that under certain conditions bodies possess the capacity for doing work. Thus, a body of water at a high level, gas under pressure in a tank, steam confined in a steam boiler, and the air moving as a wind, are all able to do work by means of appropriate motors. In general, a body or system *on which work has been done* acquires increased capacity for doing work. It is then said to possess more *energy* than before.

[1] From the noted English engineer James Watt.

"Work may be considered as the transference of energy from one body or system to another." "Energy we know only as that which in all natural phenomena is constantly passing from one portion of matter to another." Since the work done on a body is the measure of its increase of energy, work and energy are measured in the same units.

159. Potential Energy. — A mass of compressed air in an air gun tends to expand; it possesses energy and may expend it in propelling a bullet. Energy is stored also in the lifted weight of the pile driver (Fig. 132), the coiled spring of the clock, the bent bow of the archer, the impounded waters behind a dam, the chemical changes in a charged storage battery, and the mixed charge of gasoline vapor and air in the cylinder of a gas engine.

FIGURE 132. — PILE DRIVER.

In all such cases of the storage of energy a *stress* (§ 43) is present. The compressed air pushes outward in the air gun; gravity pulls on the lifted weight; the spring tends to uncoil in the clock; the bent bow tries to unbend; the water presses against the dam; the electric pressure is ready to produce a current; and the explosive gas mixture awaits only a spark to set free its energy. The energy thus stored, which is associated with a stress or with a position with respect to some other body, is *energy of stress*, or, more commonly, *potential energy*. The energy of an elevated body, of bending, twisting, of chemical sep-

aration, and of air, steam, or water under pressure, are all examples of potential energy.

160. Kinetic Energy. — A body also possesses energy in consequence of its motion; the energy of a moving body is known as *kinetic energy*. The descending hammer forces the nail into the wood, the rushing torrent carries away bridges and overturns buildings; the swiftly moving cannon ball, by virtue of its high speed, demolishes fortifications or pierces the steel armor of a battleship; the energy stored in the massive rotating flywheel keeps the engine running and may do work after the steam is shut off. When the engine is speeding up, it pushes and pulls on the shaft to increase the speed of the flywheel; in other words, the engine does work *on* the flywheel. After normal speed has been reached, all the work done by the engine goes into the driven machinery; but if an extra load comes on the engine, its speed does not drop suddenly, because it is sustained by the flywheel giving out some of its stored energy to help along the engine. The engine tends to stop the flywheel, and this now *does* work instead of absorbing energy.

When a meteoric body, or "shooting star," enters the earth's atmosphere, its energy of motion is converted into heat by friction with the air; the heat generated raises the temperature of the meteor (at least on its surface) until it glows like a star. If it is small, it may even burn up or become fine powder.

The energy of the invisible molecular motions of bodies constituting heat is included under kinetic energy no less than that of their visible motion. Heat is a form of kinetic energy.

Kinetic energy must not be confused with force. A mass of moving matter carries with it kinetic energy, but

it exerts no force until it encounters resistance. Energy is then transferred to the opposing body, and force is exerted only during the transfer.

161. Measure of Energy. — Energy is measured in the same terms as those used in measuring work. In general, *potential energy* is the measure of the mechanical work done in storing the energy, or

$$P.E. = f \times s. \quad . \quad . \quad \text{(Equation 21)}$$

If f is in pounds of force and s in feet, the result is in foot pounds. Similarly, if f is in grams of force and s in centimeters, the potential energy is expressed in gram-centimeters.

Since a gram of force is equal to 980 dynes, expressed in ergs,

$$P.E. = 980 \times \textit{grams} \times \textit{centimeters}.$$

162. Kinetic Energy in Terms of Mass and Velocity. — The work fs done by the force f on the mass m to give it the velocity v, while working through the distance s, measures the kinetic energy acquired, or,

$$K.E. = f \times s.$$

But it is highly desirable to express kinetic energy in terms of the mass m and the acquired velocity v, instead of f and s. By the second law of motion (§ 130) $f = ma$. Hence $K.E. = ma \times s$. But $s = \frac{1}{2}at^2$. Therefore $K.E. = \frac{1}{2}ma^2t^2$. Also $v = at$ (§ 106); therefore

$$K.E. = \tfrac{1}{2}mv^2. \quad . \quad . \quad \text{(Equation 22)}$$

Both m and v are magnitudes independent of gravitation; it follows that the results calculated from Equation 22 cannot be in gravitational units. If m is expressed in grams and v in centimeters per second, the kinetic energy is in

ergs. Since the gram-centimeter is equal to 980 ergs, to reduce the result to gram-centimeters, divide by the value of g in this system, or 980.

In precisely the same way, if m is in pounds and v in feet per second, to obtain the energy in foot pounds, divide by the value of g in the English system, 32.2.

To illustrate: If an automobile, weighing 3000 lb., is running at a speed of 30 miles per hour, find its kinetic energy.

A mile a minute is 88 ft. per second, and 30 miles an hour or half a mile a minute is 44 ft. per second. Hence the kinetic energy of the moving car is

$$\frac{3000 \times 44^2}{2 \times 32.2} = 90{,}186 \text{ ft. lb.}$$

This energy represents very nearly the work required to lift the car 30 ft. high against gravity, for this work is

$$3000 \times 30 = 90{,}000 \text{ ft. lb.}$$

A large ship, moving toward a wharf with a motion scarcely perceptible, will crush with great force small intervening craft. The moving energy of the large vessel is great because of its enormous mass, even though its velocity is small. Its *weight* is supported by the water and has nothing to do with its crushing force.

163. Transformations of Energy. — When a bullet is shot vertically upward, it gradually loses its motion and its kinetic energy, but gains energy of position or potential energy. When it reaches the highest point of its flight, its energy is all potential. It then descends, and gains energy of motion at the expense of energy of position. The one form of energy is, therefore, convertible into the other.

The pendulum illustrates the same principle. While the bob is moving from the lowest point of its path toward either extremity, its kinetic energy is converted into potential energy; the reverse transformation sets in

when the pendulum reverses its motion. All physical processes involve energy changes, and such changes are in ceaseless progress.

164. Conservation of Energy. — Whenever a body gains energy as the result of work done on it, it is always at the expense of energy in some other body or system. The agent, or body, which does work always loses energy; the body which has work done on it gains energy equal to the work done. On the whole there is neither gain nor loss of energy, but only its transfer from one body to another. Innumerable facts and observations show that it is as impossible to create energy as it is to create matter. So the law of *conservation of energy* means that *no energy is created and none destroyed by the action of forces we know anything about.*

Closed Jaws of Ore Bucket.

This crane makes one trip per minute from the hold of the vessel to the ore train on the dock.

165. Dissipation of Energy. — Potential energy is the more highly available or useful form of energy. It always tends to go over into the kinetic type, but in such a way that only a portion of the kinetic energy is available to effect useful changes in nature or in the mechanic arts.

The remainder is dissipated as heat. ***This running down of energy by passing into an unavailable form is known as the dissipation of energy.*** It was first recognized and distinctly stated by Lord Kelvin in 1859.

The capacity which a body possesses for doing work does not depend on the total quantity of energy which it may possess, but only on that portion which is ***available***, or is capable of being transferred to other bodies. In the problems of physics our chief concern is with the variations of energy in a body and not with its total value.

Questions and Problems

1. A cord that will just support an iron ball will generally break if the attached ball is lifted and allowed to drop. Explain.

2. In what form is the energy of a coiled spring? Of a bomb? Of a pile driver?

3. Lake Tahoe, in the Sierra Nevadas, is at an elevation of 6225 ft. above the sea. Account for the energy of position stored there in the water.

4. Why has the ball in leaving the gun so much more energy of motion than the gun has in its recoil?

5. Why is "perpetual motion" impossible?

6. Is not the case of the earth going around the sun a case of perpetual motion? How does this differ from what is commonly meant by "perpetual motion"?

7. A rectangular slab of marble 6 ft. 3 in. long and 3 in. thick, and weighing 500 lb., lies on a level floor. How much work in foot pounds must be done to set it vertically on end?

8. A barrel of flour weighs 196 lb. How much work must be done in taking it up an elevator to a height of 50 ft.?

9. How much work against gravity does a man weighing 150 lb. do in climbing a hill 200 ft. high?

10. A brick weighs 7 lb. A hod carrier takes 12 at a load and carries them to the top of the building 50 ft. high. If he works eight hours a day and makes four trips per hour, how many foot pounds of work does he do in addition to lifting himself?

Lord Kelvin (Sir William Thomson), 1824–1907, was born at Belfast. He graduated at Cambridge in 1845 and in the same year received the appointment of professor of natural philosophy in the University of Glasgow, a position which he held for fifty-three years. He was one of the greatest mathematical physicists of his day. His invention of the astatic mirror galvanometer and the siphon recorder has made successful marine cables a reality. His laboratory for the use of students was the first of the kind to be established. His most noteworthy investigations were in heat, energy, and electricity, yet there is scarcely any portion of physical science that has not been greatly enriched by his genius.

11. A pull of 50 lb. of force pulls a 200 lb. truck 300 ft. on a level floor. How much work in foot pounds is done?

12. A thousand barrel tank at a mean level of 75 ft. is filled with water. How much work is done in filling it, assuming a barrel of water to weigh 260 lb.? How long would it take a motor, working at a rate of 2 H.P., to pump it full?

13. A gallon of water weighs $8\frac{1}{3}$ lb. How much work is done in pumping 5,000,000 gallons to an elevation of 300 ft.?

14. A 10 lb. ball fired from a cannon has an initial velocity of 2000 ft. per second. Calculate its kinetic energy in foot pounds.

15. A loaded sled with a total mass of 1200 lb. coasts down a hill and acquires a speed of 40 ft. per second at the foot of the hill. Calculate its kinetic energy when it reaches the bottom.

16. A body whose mass is 25 kg. is moving with a speed of 5 m. per minute. What is its kinetic energy in joules?

17. A force of 100 g. moves a mass of 1000 g. against gravity through a vertical distance of 100 m. in 10 sec. Express the activity of the agent in watts.

18. An electric force pump working at the rate of 10 K.W. is employed to raise water to a height of 50 m. How many liters of water can the pump raise in an hour?

19. An automobile weighing 3000 lb. and running at the rate of 30 mi. per hour is brought to rest by the brakes within a distance of 40 ft. What is the force of the brakes?

20. How many H.P. are transmitted by a rope passing over a wheel 33 ft. in circumference and making one revolution per second, the tension in the rope being 100 lb. of force?

II. MACHINES

166. What a Machine is. — A *machine* is a device designed to change the direction or the value of a force required to do useful work, or one to transform and transfer energy.

Simple machines enable us to do many things that would be impossible for us to do without them. A boy can draw a nail with a claw

hammer (Fig. 133); without it and with his fingers alone he could not start it in the least. By the use of a single pulley, the direction of the force applied may be changed, so as to lift a weight, for example, while the force acts in any convenient direction. Two men can easily lift a piano up to a second story window with a rope and tackle. Perhaps the most important use of machines is for the purpose of utilizing the forces exerted by animals, and by wind, water, steam, or electricity. A water wheel transforms the potential and kinetic energy of falling water into mechanical energy represented by the energy of the rotating wheel. A dynamo electric machine transforms mechanical energy into the energy of an electric current, and an electric motor at a distance transforms the electric energy back again into useful mechanical work.

FIGURE 133. — HAMMER AS LEVER.

167. General Law of Machines. — Every machine must conform to the principle of the conservation of energy; that is, *the work done by the applied force equals the work done in overcoming the resistance*, except that some of the applied energy may be dissipated as heat or may not appear in mechanical form. A machine can never produce an increase of energy so as to give out more than it receives.

Denote the applied force, or *effort*, by E and the *resistance* by R, and let D and d denote the distances respectively through which they work. Then from the law of conservation of energy, the effort multiplied by the distance through which it acts is equal to the resistance multiplied by its displacement, or

$$ED = Rd. \quad . \quad . \quad . \quad \text{(Equation 23)}$$

168. Friction. — *Friction is the resistance which opposes an effort to slide or roll one body over another.* It is called into action whenever a force is applied to make one surface

move over another. Friction arises from irregularities in the surfaces in contact and from the force of adhesion. It is diminished by polishing and by the use of lubricants.

Experiments show that friction (*a*) is proportional to the pressure between the surfaces in contact, (*b*) is inde-

FRENCH MACHINE FOR DIGGING TRENCHES.

pendent of the area of the surfaces in contact within certain limits, and (*c*) has its greatest value just before motion takes place. The friction of a solid rolling on a smooth surface is less than when it slides. Advantage is taken of this fact to reduce the friction of bearings. A ball-bearing (Fig. 134) substitutes the rolling friction between balls and rings for the sliding friction between a shaft and its journal.

FIGURE 134.— BALL-BEARING.

FIGURE 135. — ROLLER BEARING.

Roller bearings (Fig. 135) are also used with similar advantages.

169. Advantages and Disadvantages of Friction. — Friction has innumerable uses in preventing motion between surfaces in contact. Screws and nails hold entirely by friction; we are able to walk because of friction between the shoe and the pavement; shoes with nails in the heels are dangerous on cast-iron plates because the friction between smooth iron surfaces is small. Friction is useful in the brake to stop a motor car or railway train, in holding the driving wheels of a locomotive to the rails, and in enabling a gasoline engine to drive an automobile by friction between the tires and the street.

STEAM TRACTOR.

Notice the ridges on the driving wheels to increase the friction with the earth.

On the other hand, friction is also a resistance opposing useful motion, and whenever motion takes place, work must be done against

this frictional resistance. The energy thus consumed is converted into heat and is no longer available for useful work.

170. Efficiency of Machines. — On account of the impossibility of avoiding friction, every machine wastes energy. The work done is, therefore, partly *useful* and partly *wasteful*. *The efficiency of a machine is the ratio of the useful work done by it to the total work done by the acting force,*

or $$efficiency = \frac{useful\ work\ done}{total\ energy\ applied}.$$

For example, an effort of 100 pounds of force applied to a machine produces a displacement of 40 ft. and raises a weight of 180 lb. 20 ft. high. Then $100 \times 40 = 4000$ ft. lb. of energy are put into the machine, and the work done is $180 \times 20 = 3600$ ft. lb.

Hence $$efficiency = \frac{3600}{4000} = 0.9 = 90 \text{ per cent.}$$

Ten per cent of the energy is wasted and ninety per cent recovered.

Since every machine wastes energy, a machine which will do either useful or useless work continuously without a supply of energy from without, a so-called "perpetual motion machine," is thus clearly impossible.

Let e denote the efficiency of a machine; then from the relations just explained, Equation 23 becomes

$$eED = Rd. \quad . \quad . \quad . \quad \text{(Equation 24)}$$

This relation is the strictly correct one to apply to all machines; but in most problems dealing with simple machines, friction is neglected.

171. Simple Machines. — All machines can be reduced to six *mechanical powers* or *simple machines:* the *lever*, the *pulley*, the *inclined plane*, the *wheel and axle*, the *wedge*, and the *screw*. Since the wheel and axle is only a modi-

fied lever, and the wedge and the screw are modifications of the inclined plane, the mechanical powers may be reduced to three.

In solving problems relating to simple machines in elementary physics it is customary to neglect friction and to consider that the parts of machines are rigid and without weight. With these limitations, the law expressed by Equation 23 holds good.

172. Mechanical Advantage. — A man working a pump handle and pumping water is an agent *applying energy;* the pump and the water compose a system *receiving energy.* In a simple machine the force exerted by the agent applying energy, and the opposing force of the system receiving energy, may be denoted by the two terms, *effort,* E, and *resistance,* R. The problem in simple machines consists in finding the ratio of the resistance to the effort.

The ratio of the *resisting force R to the applied force E is called the mechanical advantage of the machine.* This ratio may always be expressed in terms of certain parts of simple machines.

173. Moment of a Force. — In the application of the lever, the pulley, or the wheel and axle there is motion about an axis. The application of a single force to a body with a fixed axis produces rotation only. Examples are a door swinging on its hinges and the flywheel of an engine.

The effect of a force in producing rotation depends, not only on the value of the force, but on the distance of its line of application from the axis of rotation. A smaller force is required to close a door when it is applied at right angles to the door at the knob than when it is applied near the hinge. Also, an increase in the speed of rotation of a flywheel may be secured either by increasing the

applied force or by lengthening the crank. Both these elements of effectiveness are included in what is known as the *moment of a force.*

The moment of a force is the product of the force and the perpendicular distance between its line of action and the axis of rotation. Let M be a body which may rotate about an axis through O (Fig. 136). The moment of the force F applied at B in the direction CB is $F \times OB$; applied in the direction AB, its moment is $F \times OA$. The point O is called the *center of moments.*

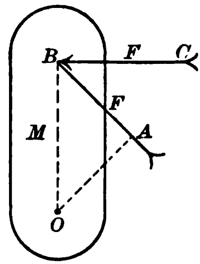


FIGURE 136. — MOMENT OF FORCE.

A moment is considered positive if it produces rotation in a clockwise direction, and negative if in the other. *If the sum of the positive moments equals that of the negative moments, there is equilibrium.*

The principle of moments is a very useful one in solving a great variety of problems.

174. The Lever. — The lever is more frequently used than any other simple machine. In its simplest form *the lever is a rigid bar turning about a fixed axis called the fulcrum.* It is convenient to divide levers into three classes, distinguished by the relative position of the fulcrum with respect to the two forces. In the *first class* the fulcrum is between the effort E and the resistance R (Fig. 137); in the *second class* the resistance is between the effort and the fulcrum; in

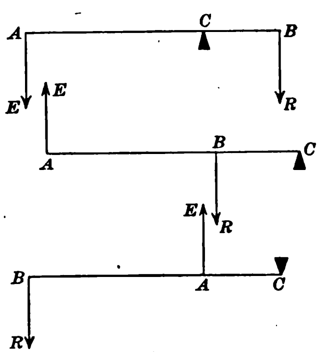


FIGURE 137. — LEVERS.

the *third class* the effort is between the resistance and the fulcrum.

FIGURE 138. — LEVER, FIRST CLASS.

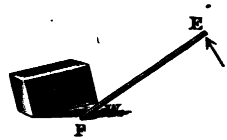


FIGURE 139. — LEVER, SECOND CLASS.

175. Examples of Levers. — A *crowbar* used as a pry (Fig. 138) is a lever of the first class, but when used to lift a weight with one end on the ground (Fig. 139), it is a lever of the second class. *Scissors* (Fig. 140) are double levers of the first class. So also are the *tongs* of a blacksmith, and those used in chemical laboratories for lifting crucibles (Fig. 141). The *forearm* when it supports a weight in the extended hand (Fig. 142), and the *door* when it is closed by pushing it near the hinge, are examples of levers of the third class. *Nut-crackers* (Fig. 143) and *lemon squeezers* are double levers of the second class.

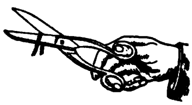


FIGURE 140. — SCISSORS.

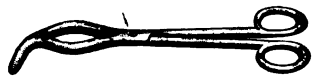


FIGURE 141. — TONGS.

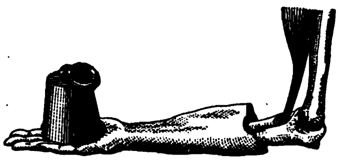


FIGURE 142. — FOREARM AS LEVER.

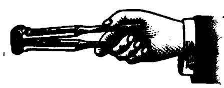


FIGURE 143. — NUT CRACKER.

The *steelyard* (Fig. 144) is a lever of the first class with unequal arms. The *common balance* (Fig. 145) is a lever of the first class with equal arms. The two weights are thus also equal. The conditions for a sensitive balance, to show a small excess of weight in one pan over that in the other, are small friction at the fulcrum, a light beam, and the center of gravity only slightly lower than the "knife-edge" forming the fulcrum.

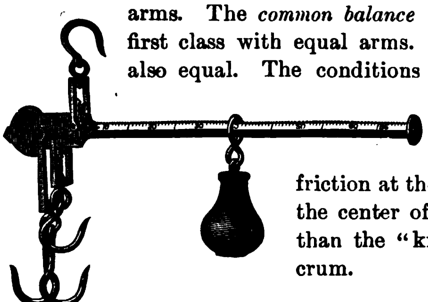


FIGURE 144. STEELYARD.

176. Mechanical Advantage of the Lever. — In Fig. 146 E is the effort, R the resistance or

weight lifted, C the fulcrum, and AC and BC the lever arms. Consider the lever to be weightless and to rotate about C without friction; then the moment of the force E about the fulcrum (§ 173) is $E \times AC$, and that of the force R is $R \times BC$. These two forces tend to produce rotation in opposite directions; for equilibrium their moments are therefore equal, that is, $E \times AC = R \times BC$; from which

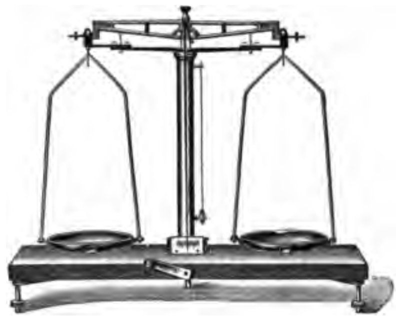


FIGURE 145. — COMMON BALANCE.

$$\frac{R}{E} = \frac{AC}{BC}. \qquad \text{(Equation 25)}$$

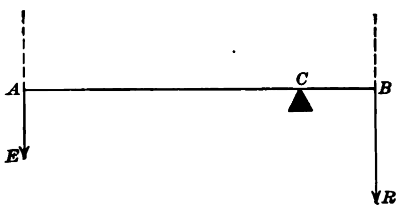


FIGURE 146. — MECHANICAL ADVANTAGE OF LEVER.

Hence, *the mechanical advantage of the lever equals the inverse ratio of its arms.*

If the weight of the lever has to be taken into account, it is to be treated as a force acting at the center of gravity of the lever, and its moment must be added to that of the force turning the lever in the same direction as its own weight.

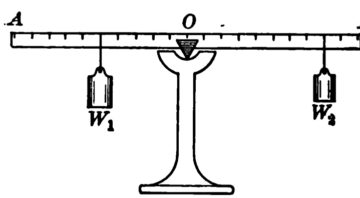


FIGURE 147.

EXAMPLE. The weights W_1 and W_2 are placed at distances 5 and 8 units respectively from O (Fig. 147). If W_1 is 20 lb., what must W_2 be for equilibrium? By the principle of moments about O,

$$20 \times 5 = W_2 \times 8;$$

whence

$$W_2 = 12.5 \text{ lb.}$$

If the lever is uniform, it is balanced about the fulcrum O and its moment is zero. Suppose the weight of the bar to be 1 lb. and its center of gravity 4 units to the left of O. The equation for equilibrium would then be

$$20 \times 5 + 1 \times 4 = W_2 \times 8.$$

Whence

$$W_2 = 13 \text{ lb.}$$

177. The Wheel and Axle consists of a cylinder and a wheel of larger diameter usually turning together on the same axis. In Fig. 148 the axle passes through C, the radius of the cylinder is BC, and that of the wheel is AC. The weights P and W are suspended by ropes wrapped around the circumference of the two wheels; their moments about the axis O are $P \times AC$ and $W \times BC$ respectively. For equilibrium these moments are equal, that is, $P \times AC = W \times BC$. Hence,

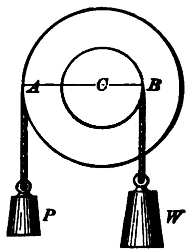


FIGURE 148. — WHEEL AND AXLE.

$$\frac{W}{P} = \frac{AC}{BC} = \frac{R}{r}. \quad \text{(Equation 26)}$$

R and r are the radii of the wheel and the axle respectively. The weight P represents the effort applied at the circumference of the wheel, and the weight W the resistance at the circumference of the axle. Therefore, *the mechanical advantage of the wheel and axle is the ratio of the radius of the wheel to that of the axle.*

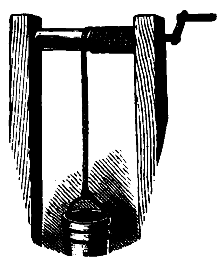


FIGURE 149. — WELL WINDLASS.

178. Applications. — The old *well windlass* for drawing water from deep wells (Fig. 149) by means of a rope and bucket is an ap-

plication of the principle of the wheel and axle. In the windlass a crank takes the place of a wheel and the length of the crank is the radius of the wheel.

FIGURE 150. — CAPSTAN.

In the *capstan* (Fig. 150) the axle is vertical, and the effort is applied by means of handspikes inserted in holes in the top.

The *derrick* (Fig. 151) is a form of wheel and axle much used for raising heavy weights. In the form shown it is essentially a double wheel and axle. The axle of the first system works upon the wheel of the second by means of the spur gear. *The mechanical advantage of such a compound machine is the ratio of the product of the radii of the wheels to the product of the radii of the axles.* In the case of gearing, the number of teeth is substituted for the radius.

FIGURE 151. — DERRICK.

FIGURE 152. — BLOCK AND SHEAVE.

179. The Pulley *consists of a wheel, called a sheave, free to turn about an axle in a frame, called a block* (Fig. 152). The effort and the resistance are attached to a rope which moves in a groove cut in the circumference of the wheel. A simple *fixed pulley* is one whose axis does not change its position; it is used to change the direction of the applied force (Fig. 153). If friction and the rigidity of the rope are neglected, the tension in the rope is everywhere the

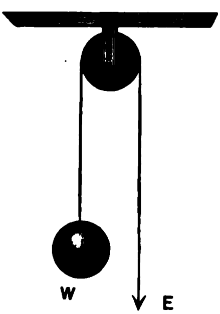


FIGURE 153. — SINGLE PULLEY.

PRACTICAL USE OF DERRICKS.
These enormous derricks are used for raising the huge blocks of marble from the quarry.

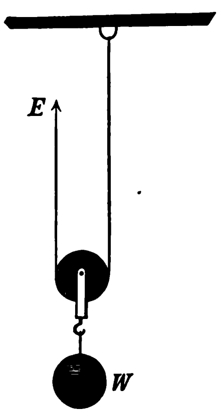


FIGURE 154. — MOVABLE PULLEY.

same; the effort and the resistance are then equal to each other and the mechanical advantage is unity.

In the movable pulley (Fig. 154) it is evident that the weight W is supported by two parts of the cord, one half of it by means of the hook fixed in the beam above and the other half by the effort E applied at the free end of the cord. If the weight is lifted, it rises only half as fast as the cord travels.

180. Systems of Fixed and Movable Pulleys. — Fixed and movable pulleys

are combined in a great variety of ways. The most common is the one employing a continuous cord with one free end and the other attached to a rigid support or to one of the blocks. Figure 155 represents a combination of one fixed and one movable pulley. Figure 156 illustrates the common "block and tackle," where each block has more than one sheave.

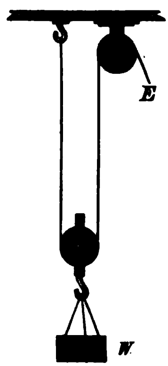


FIGURE 155. — FIXED AND MOVABLE PULLEYS.

181. Mechanical Advantage of the Simple Pulley. — In Fig. 157 the cord passes in succession around each pulley. It is evident that if the movable pulley and the resistance W are moved toward the fixed pulley a distance a, each cord passing between the two blocks must be shortened by a units. The effort E therefore travels through a distance of na units, n being the number of parts to the cord between the two pulleys. Then by the general law of machines (§ 167),

$$E \times na = W \times a;$$

whence $$\frac{W}{E} = n. \qquad \text{(Equation 27)}$$

Hence, *when a continuous cord is used, the mechanical advantage of the pulley is equal to the number of times the cord passes to and from the movable block.*

FIGURE 156. — BLOCK AND TACKLE.

It should be noticed that n is equal to the entire number of sheaves in the fixed and movable blocks, or to that

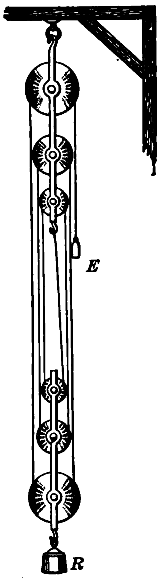


FIGURE 157. — MULTIPLE PULLEYS.

number plus one. If the upper block in Fig. 157 were the movable one, that is, if the system were inverted, so that the effort E is upward, n would be equal to one more than the number of sheaves.

182. The Differential Pulley. — The *differential pulley* (Fig. 158) is much used for lifting heavy machinery by means of a relatively small force. In the upper block are two sheaves of different diameters turning rigidly together. The lower block has only one sheave. An endless chain runs over the three sheaves in succession. It is kept from slipping by projections on the sheaves, which fit between the links of the chain. A practical advantage of the differential pulley is that there is always enough friction to keep the weight from dropping when there is no force applied to the chain.

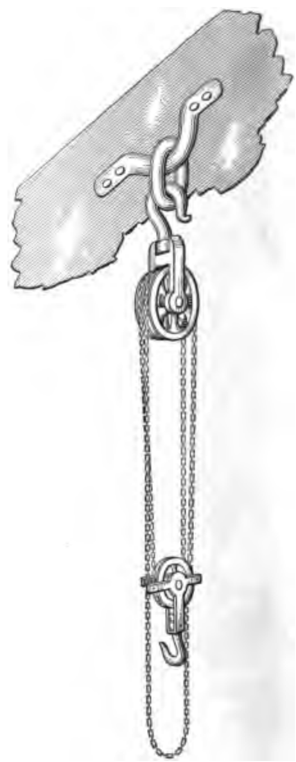


FIGURE 158. — DIFFERENTIAL PULLEY.

The mechanical advantage of the differential pulley may be found as follows: In Fig. 159, which is an outline drawing of this pulley, let the radius AC of the larger sheave be denoted by R, and that

of the smaller one AB by r. Suppose a force E to move the chain some convenient distance as R; then a length r winds off the smaller sheave at B and a length R winds on the larger sheave at D. The length of chain between the two blocks is thus shortened by a length $R - r$, and the weight W is lifted a distance $\frac{1}{2}(R - r)$. The work done by the effort E is $E \times R$ and the work done on W is $W \times \frac{1}{2}(R - r)$. Neglecting friction, these expressions may be placed equal to each other, or

$$E \times R = W \times \tfrac{1}{2}(R - r).$$

Whence $$\frac{W}{E} = \frac{2R}{R - r}. \quad . \quad . \quad \text{(Equation 28)}$$

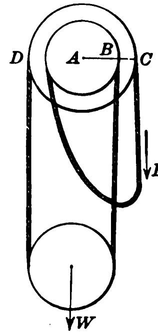


FIGURE 159. — OUTLINE OF DIFFERENTIAL PULLEY.

Since the difference $R - r$ may be made small, it is obvious that the mechanical advantage of the differential pulley is large, and it is larger the nearer r approaches R in length.

183. The Inclined Plane. — Any plane surface making an angle with the horizontal is an *inclined plane.* Planks or

FIGURE 160. — TITAN CRANE, DOVER, ENGLAND.

skids used to roll casks and barrels up to a higher level are examples of inclined planes. Every road, street, or railway not on a level is an inclined plane. The steeper the incline, the greater the push required to force the load up the grade.

If a body rests on an inclined plane without friction, the weight of the body acts vertically downward, while the reaction of the plane is perpendicular to its surface, and therefore a third force must be applied to maintain the body in equilibrium on the incline.

184. Mechanical Advantage of the Inclined Plane. — Consider only the case in which the force applied to maintain equilibrium is parallel to the *face* of the plane (Fig. 161).

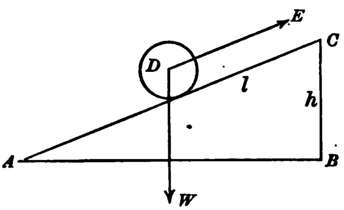


FIGURE 161. — INCLINED PLANE.

The most convenient way to find the relation between the force E and the weight W of the body D is to apply the principle of work (§ 167). Suppose D to be moved by the force E from A to C. Then the work done by E is $E \times AC$. Since the body D is lifted through a vertical distance BC, the work done on it against gravity is $W \times BC$. Therefore, $E \times AC = W \times BC$, and

$$\frac{W}{E} = \frac{AC}{BC} = \frac{l}{h}, \quad . \quad . \quad \text{(Equation 29)}$$

or *the mechanical advantage, when the effort is applied parallel to the face of the plane, is the ratio of the length of the plane to its height.*

185. Grades. — The *grade* of an inclined roadway is expressed as the number of feet rise per hundred feet along the incline. If the rise, for example, is 3 feet for every 100 feet measured along the roadway, the road has a three

per cent grade. The grade of railways seldom exceeds 2 per cent, but county roads and state highways may have 8 or 10 per cent grades. Various expedients are adopted for the purpose of lengthening the incline on roads and railways so as to keep the grades within practical limits.

THE GREAT PYRAMID.

The huge stones of which the pyramids are made were probably raised to their great height by inclined planes.

Zigzags and "switchbacks" are common expedients for the purpose.

A most remarkable inclined railway track is on the northern approach to the St. Gotthard tunnel in Switzerland. This tunnel reaches a culminating elevation of 3786 feet. In at least one instance the railway forms three turns of a screw, one above the other, each turn lying partly on the face of the mountain and partly in a tunnel cut

through the rock. This novel grade enables the road to surmount a precipice by means of an inclined plane, the necessary length of which was secured along the thread of a mammoth screw.

186. The Wedge is a double inclined plane with the effort applied parallel to the base of the plane, and usually by a blow with a heavy body (Fig. 162). Although the principle of the wedge is the same as that of the inclined plane, yet no exact statement of its mechanical advantage is possible, because the resistance has no definite relation to the faces of the planes, and the friction cannot be neglected. Many cutting instruments, such as the ax and the chisel, act on the principle of the wedge; also nails, pins, and needles.

FIGURE 162.—THE WEDGE.

187. The Screw is a cylinder, on the outer surface of which is a uniform spiral projection, called the *thread*. The faces of this thread are inclined planes. If a long triangular strip of paper be wrapped around a pencil (Fig. 163), with the base of the triangle perpendicular to the axis of the cylindrical pencil, the hypotenuse of the triangle will trace a spiral like the thread of a screw.

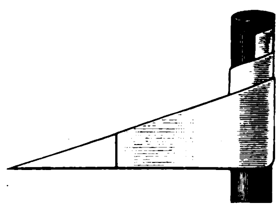


FIGURE 163.—THE SCREW.

The screw (Fig. 164) works in a block called a *nut*, on the inner surface of which is a groove, the exact counterpart of the thread.

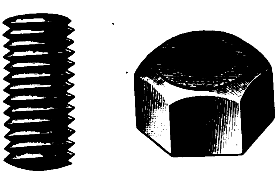


FIGURE 164.—THE NUT.

The effort is applied at the end of a lever or wrench, fitted either to the screw or to the nut. When either makes a complete turn, the screw or the nut moves through a distance equal to that between two adjacent threads, measured parallel to the axis of the screw cylinder. This distance, *s* in Figure 165, is called the *pitch* of the screw. It is usually expressed as the number of threads to the inch or to the centimeter.

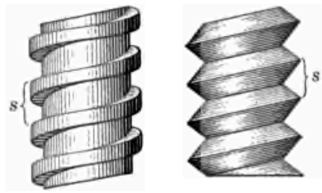


FIGURE 165. — PITCH OF SCREW.

188. Mechanical Advantage of the Screw. — Since the screw is usually combined with the lever, the simplest method of finding the mechanical advantage is to apply the principle of work, as expressed in the general law of machines (§ 167). If the pitch be denoted by s and the resistance overcome by R, then, ignoring friction, the work done against R in one revolution of the screw is $R \times s$. If the length of the lever is l, the work done by the effort E in one revolution is $E \times 2\pi l$.


FIGURE 166. — JACKSCREW.

Whence $E \times 2\pi l = R \times s$, or

$$\frac{R}{E} = \frac{2\pi l}{s}. \quad \text{(Equation 30)}$$

Hence, *the mechanical advantage of the screw equals the ratio of the distance traversed by the effort in one revolution of the screw to the pitch of the screw.*

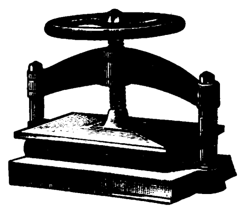


FIGURE 167. — LETTER PRESS.

189. Applications of the Screw. — The *jackscrew* (Fig. 166), the *letter press* (Fig. 167), the *vise* (Fig. 168), the two blade *propeller* of a

flying machine, and the two, three, or four blade *propeller* of a ship are familiar examples of the use of a screw. The rapid rotation of the propeller blades tends to push backward the air in the one case and the water in the other, but the inertia of the fluid medium produces a reaction against the propeller and forces the vessel forward. The screw propeller pushes against the fluid and so forces itself and the vessel to which it is attached in the other direction.

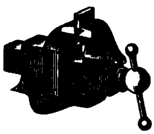


FIGURE 168. — THE VISE.

An important application of the screw, though not as a machine, is that for measuring small dimensions. The wire *micrometer* (Fig. 169) and the *spherometer* (Fig. 170) are instruments for this purpose. In both, an accurate screw has a head divided into a number of equal parts, 100 for example, so as to register any portion of a revolution. If the pitch of the screw is 1 mm., then turning the head through one of its divisions causes the screw to move parallel to its axis 0.01 mm. All wood screws, augers, gimlets, and most machine screws and bolts are right-handed, — that is, they screw in or away from the observer by turning around in the direction of watch hands. An example of a left-handed screw is the turnbuckle (Fig. 171). This has a right-handed screw at one end and a left-handed screw at the other. It is used for tightening tie rods, stays, etc. One turn of the buckle brings the rods together a distance equal to twice the pitch of the screws.

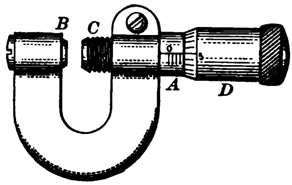


FIGURE 169. — MICROMETER.

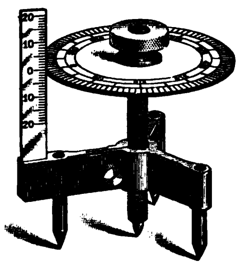


FIGURE 170. — SPHEROMETER.

Questions and Problems

1. What are the relative positions of the effort, the resistance, and the fulcrum in the following: the lever as applied to the jack-screw, the oar of a boat in rowing, the claw hammer in pulling a nail, and a bar applied to a car wheel to move the car?

FIGURE 171. — TURNBUCKLE.

2. In which direction does friction on the rails act on the wheels of a locomotive? On those of a freight car? Does it act in the same direction on the front and rear wheels of an automobile?

3. Calculate the efficiency of a machine that lifts a weight of 1000 lb. a distance of 8 ft. by the action of a force of 100 lb. through 100 ft.

4. A motor whose efficiency is 90 % delivers 10 H.P. What must be the input?

5. In a system of pulleys a tension of 100 lb. is applied to the rope and the rope is drawn 60 ft., while a weight of 500 lb. is lifted 10 ft. What is the efficiency of the system?

6. A weight of 100 lb. is lifted by a lever of the second kind. The weight is placed 2 ft. from the fulcrum and the lever is 12 ft. long. What force is necessary?

7. A bar 4 m. long is of uniform size and weighs 1 kg. to the meter. A weight of 10 kg. is placed at one end, and the fulcrum is 1 m. from that end. What weight at the other end will produce a balance?

8. In order to lift a weight of 500 lb. at one end of a bar 15 ft. long, a weight of 100 lb. is used at the other end. The bar is of uniform size and weighs 25 lb. Where must the fulcrum be placed?

9. The axle on which the rope wound in a windlass was 8 in. in diameter. The crank was 12 in. long and the weight lifted was 200 lb. What force was applied?

10. The diameter of a ship's capstan is 16 in. What force must be applied to each of two handspikes at an effective distance of 6 ft. to turn the capstan and lift an anchor weighing 2400 lb. if the efficiency of the machine is 80 per cent?

11. In a system of six pulleys, three of which are movable, how many kilograms can a force of 25 kg. support?

12. A jackscrew was used to lift a weight of 200 lb. The lever was 2 ft. long and the screw had 4 threads to the inch. Assuming an efficiency of 100 %, what force was applied at the end of the handle?

13. The radii of a wheel and the axle are 5 ft. and 5 in. respectively. It was found that a force of 100 lb. could lift a weight of 960 lb. What weight would 100 lb. of force lift if there were no friction? What is the efficiency of the machine?

14. If the front sprocket wheel of a bicycle contains 24 sprockets and the rear one 8, how far will one complete turn of the pedals drive a 28 in. wheel?

CHAPTER VII

SOUND

I. WAVE MOTION

190. Vibrations. — A *vibrating* body is one which repeats its limited motion at regular short intervals of time. A *complete* or *double vibration* is the motion between two successive passages of the moving body through any point of its path ***in the same direction.***

If we suspend a ball by a long thread and set it swinging like a common pendulum, it will return at regular intervals to the starting point. If we set the ball moving in a circle, the string will describe a conical surface and the ball will again return at the same intervals to the starting point.

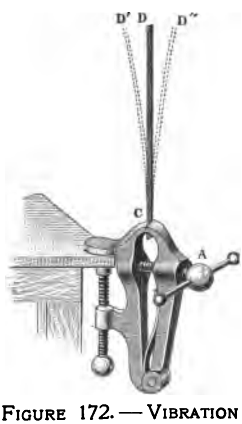


FIGURE 172. — VIBRATION OF STEEL STRIP.

191. Kinds of Vibration. — Clamp one end of a thin steel strip in a vise (Fig. 172); draw the free end aside and release it. It will move repeatedly from D' to D'' and back again. The shorter or thicker the strip, the quicker its vibration; when it becomes like the prong of a tuning fork, it emits a musical sound.

Vibrations like these are ***transverse.*** *A body vibrates transversely when the direction of the motion is at right angles to its length.* The strings of a violin, the reeds of a cabinet organ, and the wires of a piano are familiar examples.

Fasten the ends of a long spiral spring securely to fixed supports with the spring slightly stretched. Crowd together a few turns of the spiral at one end and release them. A vibratory movement will travel from one end of the spiral to the other, and each turn of wire will swing backward and forward in the direction of the length of the spiral (Fig. 173).

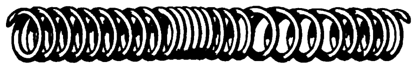


FIGURE 173. — VIBRATORY MOTION IN SPRING.

The vibrations of the spiral are longitudinal. *A body vibrates longitudinally when its parts move backward and forward in the direction of its length.* The vibrations set up in a long glass tube by stroking it lengthwise with a damp cloth are longitudinal; so are those of the air in a trumpet and the air in an organ pipe.

192. Wave Motion. — Tie one end of a soft cotton rope, such as a clothesline, to a fixed support; grasp the other end and stretch the rope horizontally. Start a disturbance by an up-and-down motion of the hand. Each point of the rope will vibrate with simple harmonic motion (§ 112), while the disturbance will travel along the rope toward the fixed end.

This progressive change of form due to the periodic vibration of the particles of the medium is a wave. The particles are not all in the same phase (§ 112) or stage of vibration, but they pass through corresponding positions *in succession.*

193. Transverse Waves. — A small camel's-hair brush is attached to the end of a long slender strip of clear wood, mounted as

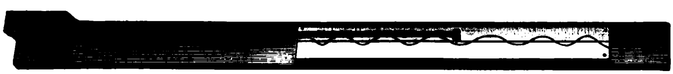


FIGURE 174. — INSCRIBING TRANSVERSE WAVE.

shown in Fig. 174, which was made from a photograph giving an oblique view of the apparatus. The brush should touch lightly the

paper attached to the narrow board, which may be moved in a straight line against the guiding strip. Ink the brush and while it is at rest push the paper along under it. The brush will mark the straight middle line running through the curve shown in the figure. Replace the board in the starting position; then pull the strip aside and release it. Again draw the board under the brush with uniform motion. This time the brush traces the curved line.

The strip of wood vibrates at right angles to the direction of motion of the paper with a simple harmonic motion (§ 112); the board moves with a uniform rectilinear motion; the curve is a *simple harmonic curve.* It is the resultant of the two motions, and illustrates a *transverse wave.* *A transverse wave is one in which the vibration of the particles in the wave is at right angles to the direction in which the wave is traveling.*

194. To Construct a Transverse Wave. — Suppose a series of particles, originally equidistant in a horizontal straight line, to

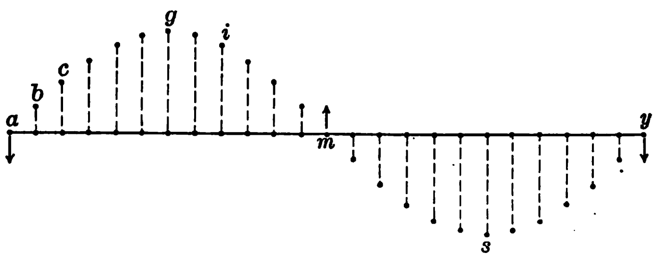


FIGURE 175. — POSITION OF PARTICLES IN WAVE.

vibrate transversely with simple harmonic motion. Let Fig. 175 represent the position of the particles at some particular instant, the displacement of each one from the straight horizontal line being found by means of an auxiliary circle as in § 112. They will outline a transverse wave. At g the particle has reached its extreme displacement in the positive direction and is momentarily at rest; the particle at s has reached its maximum negative displacement, and is also at rest. The particle at m is moving in the positive direction

with maximum velocity, and the particles *a* and *y* with maximum velocity in the negative direction. If the wave is traveling to the right, then an instant later the displacement of *g* will have diminished and that of *i* will have increased to a maximum, the crest having moved forward from *g* to *i* in the short interval. The successive particles of the wave all differ in phase by the same amount.

195. Longitudinal Wave. — Place a lighted candle at the conical end of the long tin tube of Fig. 176. Over the other end stretch a

FIGURE 176. — WAVE OF COMPRESSION IN TUBE.

piece of parchment paper. Tap the paper lightly with a cork mallet; the transmitted impulse will cause the flame to duck, and it may easily be blown out by a sharper blow.

The air in the tube is agitated by a vibratory motion, and a wave, consisting of a compression followed by a rarefaction, traverses the tube. The dipping of the flame indicates the arrival of the compression. Each particle of air vibrates longitudinally in the tube, the disturbance being similar to that of the vibrating spiral.

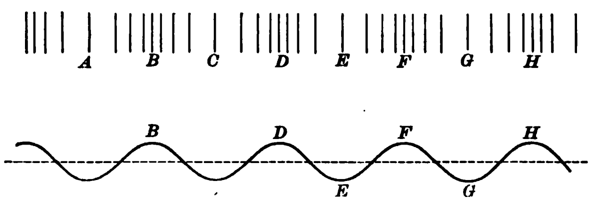


FIGURE 177. — PARTICLES IN WAVE OF COMPRESSION.

Figure 177 illustrates the distribution of the air particles when disturbed by such a longitudinal wave of compressions and rarefactions. *B*, *D*, *F*, etc., are regions of compressions; *A*, *C*, *E*, etc., those of rarefaction. The

distances of the different points of the curve from the straight line denote the relative velocities of the air particles. The greatest velocity forward is at the middle of the condensation, as at B, and the greatest velocity backward is at the middle of the rarefaction, as at A. A and C, or B and D, are in the same *phase*, that is, in corresponding positions in their path.

A longitudinal wave is one in which the vibrations are backward and forward in the same direction as the wave is traveling.

196. Wave Length. — The *length of a wave* is the distance from any particle to the next one in the *same phase*, as from a to y (Fig. 175), or from A to C or B to D (Fig. 177). Since the wave form travels from a to y, or from A to C, during the time of one complete vibration of a particle, it follows that *the wave length is also the distance traversed by the wave during one vibration period.*

197. Water Waves. — One of the most familiar examples of transverse waves are those on the surface of water. For deep water

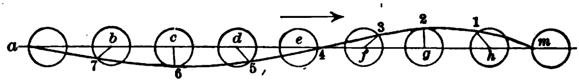


FIGURE 178. — WATER WAVE.

the particles describe circles, all in the same vertical plane containing the direction in which the wave is traveling, as illustrated in Fig. 178. The circles in the diagram are divided into eight equal arcs, and the water particles are supposed to describe these circles in the direction of watch hands and all at the same rate; but in any two consecutive circles their phase of motion differs by one eighth of a period, that is, the water particles are taken at such a distance apart that each one begins to move just as the preceding one has completed one eighth part of its orbit. When a has completed one revolution, b is one eighth of a revolution behind it, c two eighths or one quarter, etc.

Lord Rayleigh (John William Strutt) was born at Essex in 1842, and graduated from Cambridge University in 1865. In 1884 he was appointed professor of experimental physics in that institution, and three years later he was elected professor of natural philosophy at the Royal Institution of Great Britain. His work is remarkable for its extreme accuracy. The discovery of argon in the atmosphere, while attempting to determine the density of nitrogen, was the result of a very minute difference between the result obtained by using nitrogen from the air and that from another source. Nearly every department of physics has been enriched by his genius. His treatise on Sound is one of the finest pieces of scientific writing ever produced. His determination of the electrochemical equivalent of silver and the electromotive force of the Clark standard cell are contributions of the first importance to modern electrical measurements.

A smooth curve drawn through the positions of the particles in the several circles at the same instant is the outline or contour of a wave.

When a particle is at the crest of a wave, it is moving in the same direction as the wave; when it is in the trough, its motion is opposite to that of the wave.

The crests and troughs are not of the same size, and the larger the circles (or amplitude), the smaller are the crests in comparison with the troughs. Hence the crests of high waves tend to become sharp or looped, and they break into foam or white caps.

II. SOUND AND ITS TRANSMISSION

198. Sound *may be defined as that form of vibratory motion in elastic matter which affects the auditory nerves, and produces the sensation of hearing.* All the external phenomena of sound may be present without any ear to hear. Sound should therefore be distinguished from hearing.

199. Source of Sound. — If we suspend a small elastic ball by a thread so that it just touches the edge of an inverted bell jar, and strike the edge of the jar with a felted or cork mallet, the ball will be repeatedly thrown away from the jar as long as the sound is heard. This shows that the jar is vibrating energetically.

Stretch a piano wire over the table and a little above it. Draw a violin bow across the wire, and then touch it with the suspended ball of the previous paragraph. So long as the wire emits sound the ball will be thrown away from it again and again.

If a mounted tuning fork (Fig. 179) is sounded, and a light ball of pith or ivory, suspended by a thread, is brought in contact with one of the prongs at the back, it will be briskly thrown away by the energetic vibrations of the fork.

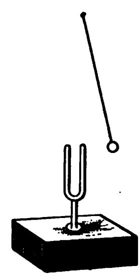


FIGURE 179. — VIBRATION OF TUNING FORK.

Partly fill a glass goblet with water, and produce a musical note by drawing a bow across its edge. The tremors of the glass will throw the surface of the water into violent agitation in four sectors, with intermediate regions of relative repose. This agitation disappears when the sound ceases.

A glass tube, four or five feet long, may be made to emit a musical sound by grasping it by the middle and briskly rubbing one end with a cloth moistened with water. The vibrations are longitudinal, and may be so energetic as to break the tube into many narrow rings.

Experiments like these show that the sources of sound are bodies in a state of vibration. Sound and vibratory movement are so related that one is strong when the other is strong, and they diminish and cease together.

200. Media for Transmitting Sound. — Suspend a small electric bell in a bell jar on the air pump table (Fig. 180). When the air is exhausted, the bell is nearly inaudible. Sound does not travel through a vacuum.

FIGURE 180. — BELL IN VACUUM.

Fasten the stem of a tuning fork to the middle of a thin disk of wood. Set the fork vibrating, and hold it with the disk resting on the surface of water in a tumbler, standing on a table. The sound, which is scarcely audible when there is no disk attached to the fork, is now distinctly heard as if coming from the table.

Hold one end of a long, slender wooden rod against a door, and rest the stem of a vibrating fork against the other end. The sound will be greatly intensified, and will come from the door as the apparent source.

Press down on a table a handful of putty or dough, and insert in it the stem of a vibrating fork; the vibrations will not be conveyed to the table to an appreciable extent.

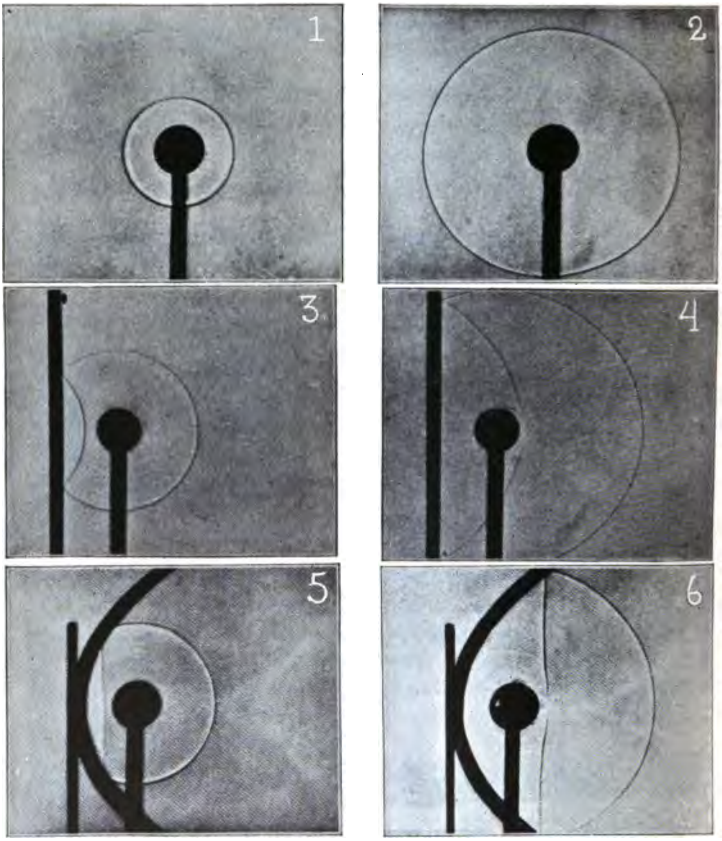
Only elastic matter transmits sound, and some kinds transmit it better than others.

201. Transmission of Sound to the Ear. — Any uninterrupted series of elastic bodies will transmit sound to the ear, be they solid, liquid, or gaseous.

A bell struck under water sounds painfully loud if the ear of the listener is also under water. A diver under water can hear voices in the air. By placing the ear against the steel rail of a railway, two sounds may be heard, if the rail is struck some distance away: a

Photographs of Sound-Waves produced by an Electric Spark behind a Black Disk.

(Taken by Professor Foley of Indiana University.)



1. A spherical sound-wave.
2. The same wave a fraction of a second later.
3. Spherical sound-wave reflected from a plate of plane glass.
4. The same wave a moment later. The broken line near the black disk shows the effect of the puff of hot air from the spark.
5. Sound-wave reflected from a parabolic reflector. The source is at the focus and the reflected wave is plane.
6. The same wave a moment later, showing its central portion advanced by the puff of hot air from the spark.

louder one through the rails and then another through the air. The faint scratching of a pin on the end of a long stick of timber, or the ticking of a watch held against it, may be heard very distinctly if the ear is applied to the other end.

The earth conducts sound so well that the stepping of a horse may be heard by applying the ear to the ground. This is understood by the Indians. The firing of a cannon at least 200 miles away may be heard in the same way. The report of a mine blast reaches a listener sooner through the earth than through the air.

The great eruption of Krakatoa in 1883 gave rise to gigantic sound waves, which produced at a distance of 2000 miles a report like the firing of heavy guns.

202. Sound Waves. — When a tuning fork or similar body is set vibrating, the disturbances produced in the air about it are known as *sound waves.* They consist of a series of condensations and rarefactions succeeding each other at regular intervals. Each particle of air vibrates in a short path in the direction of the sound transmission. Its vibrations are *longitudinal* as distinguished from the *transverse* vibrations in water waves.

203. Motion of the Particles of a Wave. — The motion of the particles of the medium conveying sound is distinct from the motion of the sound wave. A sound wave is composed of a condensation followed by a rarefaction. In the former the particles have a forward motion in the direction in which the sound is traveling; in the latter they have a backward motion, while at the same time both condensation and rarefaction travel steadily forward.

The independence of the two motions is aptly illustrated by a field of grain across which waves excited by the wind are coursing. Each stalk of grain is securely anchored to the ground, while the wave sweeps onward. The heads of grain in front of the crest are rising, while all those behind the crest and extending to the bottom of the trough are falling. They all sweep forward and backward, not *simultaneously,* but *in succession,* while the wave itself travels continuously forward.

III. VELOCITY OF SOUND

204. Velocity in Air. — In 1822 a scientific commission in France made experiments to ascertain the velocity of sound in air. Their method was to divide into two parties at stations a measured distance apart, and to determine the interval between the observed flash and the report of

VIEW OF LAKE GENEVA.

a cannon fired alternately at the two stations. The mean of an even number of measurements eliminated very nearly the effect of the wind. The final result was 331 m. per second at 0° C. The defect of the method is that the perception of sound and of light are not equally quick, and they vary with different persons.

Subsequent observers, employing improved methods, and correcting for all sources of error, have obtained as the most probable velocity 332.4 m., or 1090.5 ft., per second at 0° C. At higher temperatures sound travels

faster, the correction being 0.6 m., or nearly 2 ft., per degree Centigrade. At 20° C. (68° F.) the velocity is very nearly 1130 ft. per second.

205. Velocity in Water. — In 1827 Colladon and Sturm, by a series of measurements in Lake Geneva, found that sound travels in water at the rate of 435 m. per second at a mean temperature of 8.1° C. They measured with much care the time required for the sound of a bell struck under water to travel through the lake between two boats anchored at a distance apart of 13,487 m. It was 9.4 seconds.

A system of transmitting signals through water by means of submerged bells is in use by vessels at sea and for offshore stations. Special telephone receivers have been devised to operate under water and to respond to these sound signals. Indeed, the vessel itself acts as a sounding board and as a very good receiver.

206. Velocity in Solids. — The velocity of sound in solids is in general greater than in liquids on account of their high elasticity as compared with their density. The velocity in iron is 5127 m. per second; in glass 5026 m. per second; but in lead it is only 1228 m. per second, at a temperature in each case of 0° C.

Questions and Problems

1. Why do the timers in a 200-yd. dash start their stop watches by the flash of the pistol rather than by the report?

2. If the flash of a gun is seen 3 sec. before the report is heard, how far is the gun from the observer, the temperature being 20° C.?

3. The interval between seeing a flash of lightning and hearing the thunder was 5 sec.; the temperature was 25° C. How far away was the lightning discharge?

4. Signals given by a gun 2 mi. away would be how much in error when the temperature is 20° C. and the wind is blowing 10 mi. an hour in the direction from the listener to the gun?

5. A man sets his watch by a steam whistle which blows at 12 o'clock. The whistle is 1.5 mi. away and the temperature 15° C. How many seconds will the watch be in error?

6. A ball fired at a target was heard to strike after an interval of 8 sec. The distance of the target was 1 mi. and the temperature of the air 20° C. What was the mean velocity of the ball?

7. The distance between two points on a straight stretch of railway is 2565 m. An observer listens at one of these points and a blow is struck on the rails at the other. If the temperature is 0° C., what is the interval between the arrival of the two sounds, one through the rails and the other through the air?

8. A man watching for the report of a signal gun saw the flash 2 sec. before he heard the report. If the temperature was 0° C. and the distance of the signal gun was 2225 ft., what was the velocity of the wind?

9. A shell fired at a target, distance half a mile, was heard to strike it 5 sec. after leaving the gun. What was the average speed of the bullet, the temperature of the air being 20° C.?

IV. REFLECTION OF SOUND

207. Echoes. — *An echo is the repetition of a sound by reflection from some distant surface.* A clear echo requires a vertical reflecting surface, the dimensions of which are large compared to the wave length of the sound. A cliff, a wooded hill, or the broad side of a large building may serve as the reflecting surface. Its inequalities must be small compared to the length of the incident sound waves; otherwise, the sound is diffused in all directions.

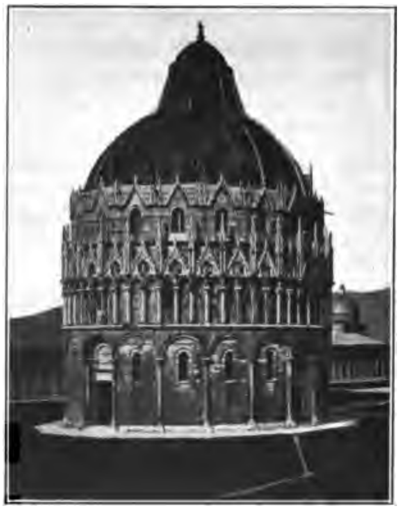
A loud sound in front of a tall cliff an eighth of a mile away will be returned distinctly after about a second and a sixth. If the reflecting surface is nearer than about fifty feet, the reflected sound tends to strengthen the original one, as illustrated by the greater distinctness of sounds indoors than in the open air. In large rooms where the echoes produce a confusion of sounds the trouble may be

Echo Bridge over the Charles near Boston.

A shout under this bridge reverberates from the bridge to the water and back over and over again.

diminished by adopting some method to prevent regular reflection, such as the hanging of draperies, or covering the walls with absorbing materials.

208. Multiple Echoes. — Parallel reflecting surfaces at a suitable distance produce *multiple echoes*, as parallel mirrors produce multiple images (§ 261). The circular baptistery at Pisa and its spherical dome prolong a sound for ten or more seconds by successive reflections; the effect is made more conspicuous by the good reflecting surface of polished marble. Extraordinary echoes sometimes occur between the parallel walls of deep cañons.



THE BAPTISTERY AT PISA.

209. Aërial Echoes. — Whenever the medium transmitting sound changes suddenly in density, a part of the energy is transmitted and a part reflected. The intensity of the reflected system is the greater the greater the difference in the densities of the two media. A dry sail reflects a part of the sound and transmits a part; when wet it becomes a better reflector and is almost impervious to sound.

Aërial echoes are accounted for by sudden changes of density in the air. Air, almost perfectly transparent to light, may be very opaque to sound. When for any reason the atmosphere becomes unstable, vertical currents

and vertical banks of air of different densities are formed. The sound transmitted by one bank is in part reflected by the next, the successive reflections giving rise to a curious prolonging of a short sound. Thus, the sound of a gun or of a whistle is then heard apparently rolling away to a great distance with decreasing loudness.

210. Whispering Gallery. — Let a watch be hung a few inches in front of a large concave reflector (Fig. 181). A place may be found for the ear at some distance in front, as at E, where the ticking of the watch may be heard with great distinctness. The sound waves, after reflection from the concave surface, converge to a point at E.

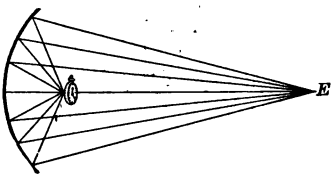


FIGURE 181. — REFLECTOR FOR SOUND.

The action of the ear trumpet depends on the reflection of sound from curved surfaces; the sides of the bell-shaped mouth reflect the sound into the tube which conveys it to the ear.

An interesting case of the reflection of sound occurs in the *whispering gallery*, where a faint sound produced at one point of a very large room is distinctly heard at some distant point, but is inaudible at points between. It requires curved walls which act as reflectors to concentrate the waves at a point. Low whispers on one side of the dome of St. Paul's in London (see page 81) are distinctly audible on the opposite side.

V. RESONANCE

211. Forced Vibrations. — A body is often compelled to surrender its natural period of vibration, and to vibrate with more or less accuracy in a manner imposed on it by an external periodic force. Its vibrations are then said to be *forced*.

Huyghens discovered that two clocks, adjusted to slightly different rates, kept time together when they stood on the same shelf. The two prongs of a tuning fork, with slightly different natural periods on account of unavoidable differences, mutually compel each other to adopt a common frequency. These two cases are examples of mutual control, and the vibrations of both members of each pair are forced.

The sounding board of a piano and the membrane of a banjo are forced into vibration by the strings stretched over them. The top of a wooden table may be forced into vibration by pressing against it the stem of a vibrating tuning fork. The vibrations of the table are forced and it will respond to a fork of any period.

212. Sympathetic Vibrations. — Place two mounted tuning forks, tuned to exact unison, near each other on a table. Keep one of them in vibration for a few seconds and then stop it; the other one will be heard to sound.

In the case of these forks, the pulses in the air reach the second fork at intervals corresponding to its natural vibration period and the effect is cumulative. The experiment illustrates *sympathetic vibrations* in bodies having the same natural period. If the forks differ in period, the impulses from the first do not produce cumulative effects on the second, and it will fail to respond.

Suspend a heavy weight by a rope and tie to it a thread. The weight may be set swinging by pulling gently on the thread, releasing it, and pulling again repeatedly when the weight is moving in the direction of the pull.

Suspend two heavy pendulums on knife-edges on the same stand, and carefully adjust them to swing in the same period. If then one is set swinging, it will cause the other one to swing, and will give up to it nearly all its own motion.

When the wires of a piano are released by pressing the loud pedal, a note sung near it will be echoed by the wire which gives a tone of the same pitch.

A number of years ago a suspension bridge of Manchester in England was destroyed by its vibrations reaching an amplitude beyond

the limit of safety. The cause was the regular tread of troops keeping time with what proved to be the natural rate of vibration of the bridge. Since then the custom has always been observed of breaking step when bodies of troops cross a bridge.

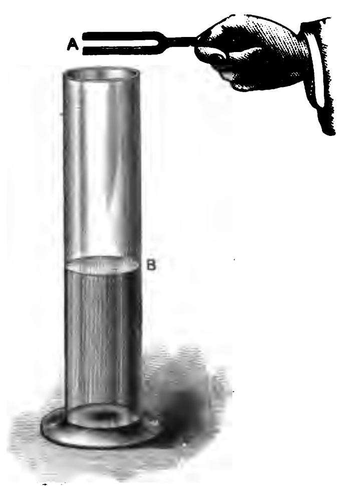


FIGURE 182. — REËNFORCEMENT OF SOUND.

213. Resonance. — *Resonance is the reënforcement of sound by the union of direct and reflected sound waves.*

Hold a vibrating tuning fork over the mouth of a cylindrical jar (Fig. 182). Change the length of the air column by pouring in water slowly. The sound will increase in loudness until a certain length is reached, after which it becomes weaker. A fork of different pitch will require a different length of air column to reënforce its sound.

The "sound of the sea" heard when a sea shell is held to the ear is a case of resonance. The mass of air in the shell has a vibration rate of its own, and it amplifies any faint sound of the same period. A vase with a long neck, or even a teacup, will also exhibit resonance.

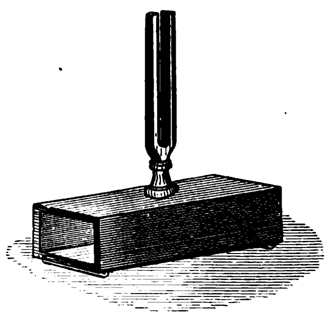


FIGURE 183. — MOUNTED TUNING FORK.

The box on which a tuning fork is mounted (Fig. 183) is a resonator, designed to increase the volume of sound. The air within the body of a violin and all instruments of like character acts as a resonator. The air in the mouth, the larynx, and the nasal passages is a resonator; the length and volume of this body of air can be changed at pleasure so as to reënforce sounds of different pitch.

214. The Helmholtz Resonator. — The resonator devised by Helmholtz is spherical in form, with two short tubes on opposite sides (Fig. 184). The larger opening *A* is the mouth of the resonator; the smaller one *B* fits in the ear. These resonators are made of thin brass or of glass, and their pitch is determined by their size. When one of them is held to the ear, it strongly reënforces any sound of its own rate of vibration, but is silent to others.

FIGURE 184. — HELMHOLTZ RESONATOR.

VI. CHARACTERISTICS OF MUSICAL SOUNDS

215. Musical Sounds. — Sounds are said to be *musical* when they are pleasant to the ear. They are caused by regular periodic vibrations. A *noise* is a disagreeable sound, either because the vibrations producing it are not periodic, or because it is a mixture of discordant elements, like the clapping of the hands.

Musical sounds have three distinguishing characteristics: *pitch*, *loudness*, and *quality*.

FIGURE 185. — SIREN.

216. Pitch. — Mount on the axle of a whirling machine (Fig. 185), or on the armature of a small electric motor, a cardboard or metal disk *D* with a series of equidistant holes in a circle near its edge. While the disk is rotating rapidly, blow a stream of air through a small tube against the circle of holes. A distinct musical tone will be produced. If the experiment be repeated with the disk rotating more slowly, or with a circle of a smaller number of holes, the tone will be lower; if the disk is rotated more rapidly, the tone will be higher.

The air passes through the holes in a succession of puffs producing waves in the air. These waves follow one another with definite rapidity, giving rise to the characteristic of sound called *pitch*. We conclude that *the pitch of a musical sound depends only upon the number of pulses which reach the ear per second.* To Galileo belongs the credit of first pointing out the relation of pitch to frequency of vibration. He illustrated it by drawing the edge of a card over the milled edge of a coin.

217. Relation between Pitch, Wave Length, and Velocity. — If a tuning fork makes 256 vibrations per second, and in that time a sound travels in air, at 20° C., a distance of 344 m., then the first wave will be 344 m. from the fork when it completes its 256th vibration. Hence, in 344 m., there will be 256 waves, and the length of each will be $\frac{344}{256}$ m., or 1.344 m. In general, then,

$$wave\ length = \frac{velocity}{frequency},$$

or in symbols, $l = \frac{v}{n}$, $v = nl$, and $n = \frac{v}{l}$. . (Equation 31)

218. Loudness. — The *loudness* of a sound depends on the intensity of the vibrations transmitted to the ear. The energy of the vibrations is proportional to the square of their amplitude; but since it is obviously impracticable to express a sensation in terms of a mathematical formula, it is sufficient to say that the loudness of a sound increases with the amplitude of vibration.

As regards distance, geometrical considerations would go to show that the energy of sound waves in the open decreases as the square of the distance increases, but the actual decrease in the intensity of sound is even greater than this. The energy of sound waves is gradually dissipated by conversion into heat through friction and viscosity.

Hermann von Helmholtz (1821–1894) was born at Potsdam. He received a medical education at Berlin and planned to be a specialist in diseases of the eye, ear, and throat. His studies soon revealed to him the need of a knowledge of physics and mathematics. To these subjects he gave his earnest attention and soon became one of the greatest physicists and mathematicians of the nineteenth century. He made important contributions to all departments of physical science. He is the author of an important work on acoustics and is celebrated for his discoveries in this field. But perhaps his most useful contribution is that of the ophthalmoscope, an instrument of inestimable value to the oculist in examining the interior of the eye.

The area of the vibrating body affects the loudness. This is illustrated in the piano, where strings of different diameters produce sounds differing in loudness. The thicker vibrating string sets more air in motion, and the wave has in consequence more energy.

The less dense the medium in which the vibration is set up, the feebler the sound. On a mountain top the report of a gun is comparable in loudness with that produced by the breaking of a stick at the base. The electric bell in a partially exhausted receiver (§ 200) is nearly inaudible.

Fill three large battery jars with coal gas, air, and carbonic acid respectively. Ring in them successively a small bell. There will be a marked difference in loudness.

219. Quality.—Two notes of the same pitch and loudness, such as those of a piano and a violin, are yet clearly distinguishable by the ear. This distinction is expressed by the term *quality* or *timbre*. Helmholtz demonstrated that the quality of a note is determined by the presence of tones of higher pitch, whose frequencies are simple multiples of that of the fundamental or lowest tone. These are known as *overtones*.

The quality of sounds differs because of the series of overtones present in each case. Voices differ for this reason. Violins differ in sweetness of tone because the sounding boards of some bring out overtones different from those of others. Even the untrained ear can readily appreciate differences in the character of the music produced by a flute and a cornet. Voice culture consists in training and developing the vocal organs and resonance cavities, to the end that purer overtones may be secured, and greater richness may by this means be imparted to the voice.

VII. INTERFERENCE AND BEATS

220. Interference. — Hold a vibrating tuning fork over a cylindrical jar adjusted as a resonator, and turn the fork on its axis until a position of minimum loudness is found. In this position cover one prong with a pasteboard tube without touching (Fig. 186). The sound will be restored to nearly maximum loudness, because the paper cylinder cuts off the set of waves from the covered prong.

FIGURE 186. — INTERFERENCE.

It is well known that the loudness of the sound of a vibrating fork held freely in the hand near the ear, and turned on its stem, exhibits marked variations. In four positions the sound is nearly inaudible. Let A, B (Fig. 187) be the ends of the two prongs. They vibrate with the same frequency, but in opposite directions, as indicated by the arrows. When the two approach each other, a condensation is produced between them, and at the same time rarefactions start from the backs at c and d. The condensations and rarefactions meet along the dotted lines of equilibrium, where partial extinction occurs, because a rare-

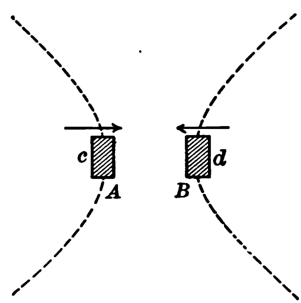


FIGURE 187. — INTERFERENCE FROM PRONGS OF TUNING FORK.

faction nearly annuls a condensation. When the fork is held over the resonance jar so that one of these lines of interference runs into the jar, the paper cylinder cuts off one set of waves, and leaves the other to be reënforced by the air in the jar.

Interference is the superposition of two similar sets of waves traversing the medium at the same time. One of the two sets of similar waves may be direct and the other reflected. If two sets of sound waves of equal length and amplitude meet in opposite phases, the condensation of one corresponding with the rarefaction of the other, the sound at the place of meeting is extinguished by interference.

221. Beats. — Place near each other two large tuning forks of the same pitch and mounted on resonance boxes. When both are set vibrating, the sound is smooth, as if only one fork were sounding. Stick a small piece of wax to a prong of one fork: this load increases its periodic time of vibration, and the sound given by the two is now pulsating or throbbing.

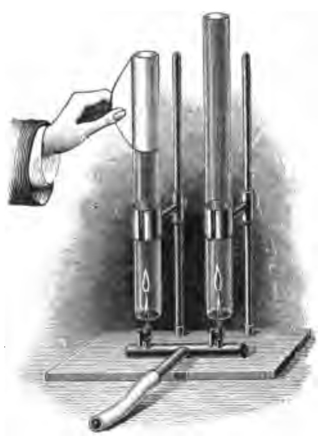


FIGURE 188. — INTERFERENCE WITH SINGING FLAMES.

Mount two organ pipes of the same pitch on a bellows, and sound them together. If they are open pipes, a card gradually slipped over the open end of one of them will change its pitch enough to bring out strong pulsations.

With glass tubes and jet tubes set up the apparatus of Fig. 188. One tube is fitted with a paper slider so that its length may be varied. When the gas flame is turned down to the proper size, the tube gives a continuous sound known as a "singing flame." By making the tubes the same length, they may be made to yield the same note, the combined sound being smooth and steady. Now change the position

of the slider, and the sound will throb and pulsate in a disagreeable manner.

These experiments illustrate the interference of two sets of sound waves of slightly different period. *The outbursts of sound, followed by short intervals of comparative silence, are called beats.*

Figure 189 illustrates the composition of two transverse waves of slightly different length. The addition of the

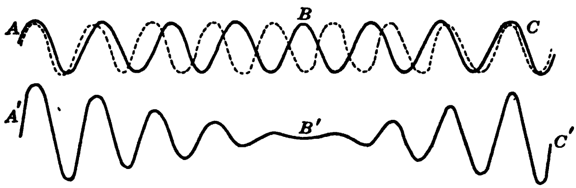


FIGURE 189. — INTERFERENCE OF TWO TRANSVERSE WAVES.

ordinates of the two waves ABC gives the wave $A'B'C'$, with a minimum amplitude at B'.

222. Number of Beats. — If two sounds are produced by forks, for example, making 100 and 110 vibrations per second respectively, then in each second the latter fork gains ten vibrations on the former. There must be ten times during each second when they are vibrating in the same phase, and ten times in opposite phase. Hence, interference of sound must occur ten times a second, and ten beats are produced. Therefore, the *number of beats per second is equal to the difference of the vibration rates (frequencies) of the two sounds.*

VIII. MUSICAL SCALES

223. Musical Intervals: — A musical interval is the relation between two notes expressed as the ratio of their frequencies of vibration. Many of these intervals have

names in music. When the ratio is 1, the interval is called *unison;* 2, an *octave;* $\frac{3}{2}$, a *fifth;* $\frac{4}{3}$, a *fourth;* etc. Any three notes whose frequencies are as 4 : 5 : 6 form a *major triad*, and alone or together with the octave of the lowest note, a *major chord.* Any three notes whose frequencies are as 10 : 12 : 15 form a *minor triad*, and alone or with the octave of the lowest, a *minor chord.*

Mount the disk of Fig. 190 on the whirling table of Fig. 185. The disk is perforated with four circles of equidistant holes, numbering 24, 30, 36, and 48 respectively. These are in the relation of 4, 5, 6, 8. Rotate with uniform speed, and beginning with the inner circle, blow a stream of air against each row of holes in succession. The tones produced will be recognized as *do, mi, sol, do'*, forming a major chord. If now the speed of rotation be increased, each note will rise in pitch, but the musical sequence will remain the same.

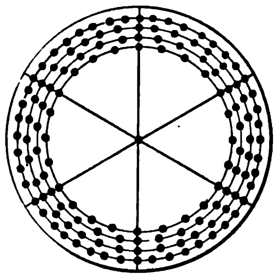


FIGURE 190. — DISK FOR MAJOR CHORD.

It will be seen from the foregoing relations that harmonious musical intervals consist of very simple vibration ratios.

224. The Major Diatonic Scale. — A *musical scale* is a succession of notes by which musical composition ascends from one note, called the *keynote*, to its octave. This last note in one scale is regarded as the keynote of another series of eight notes with the same succession of intervals. In this way the series is extended until the limit of pitch established in music is reached.

The common succession of eight notes, called the *major diatonic scale*, was adopted about three hundred and fifty years ago. The octave beginning with middle *C* is written

$$c' \quad d' \quad e' \quad f' \quad g' \quad a' \quad b' \quad c''$$

The three major triads for the keynote of C are:

$$\left.\begin{array}{ccccc} c' & : & e' & : & g' \\ g' & : & b' & : & d'' \\ f' & : & a' & : & c'' \end{array}\right\} :: 4 : 5 : 6$$

The frequency universally assigned to c' in physics is 256. It is convenient because it is a power of 2, and it is practically that of the "middle C" of the piano. If c' is due to 256, or m, vibrations per second, the frequency of the other notes of the diatonic scale may be found by proportion from the three triads above; they are as follows:

256	288	320	$341\frac{1}{3}$	384	$426\frac{2}{3}$	480	512
c'	d'	e'	f'	g'	a'	b'	c''
do	*re*	*mi*	*fa*	*sol*	*la*	*si*	*do*
m	$\frac{9}{8}m$	$\frac{5}{4}m$	$\frac{4}{3}m$	$\frac{3}{2}m$	$\frac{5}{3}m$	$\frac{15}{8}m$	$2m$

If the fractions representing the relative frequencies be reduced to a common denominator, the numerators may be taken to denote the relative frequencies of the eight notes of the scale. They are

$$24 \quad 27 \quad 30 \quad 32 \quad 36 \quad 40 \quad 45 \quad 48$$

An examination of these numbers will show that there are only three intervals *from any note to the next higher.* They are $\frac{9}{8}$, a major tone; $\frac{10}{9}$, a minor tone; and $\frac{16}{15}$, a half tone. The order is $\frac{9}{8}, \frac{10}{9}, \frac{16}{15}, \frac{9}{8}, \frac{10}{9}, \frac{9}{8}, \frac{16}{15}$.

225. The Tempered Scale. — If C were always the keynote, the diatonic scale would be sufficient for all purposes except for minor chords; but if some other note be chosen for the keynote, in order to maintain the same order of intervals, new and intermediate notes will have to be introduced. For example, let D be chosen for the key-

note, then the next note will be $288 \times \frac{9}{8} = 324$ vibrations, a number differing slightly from *E*. Again, $324 \times \frac{10}{9} = 360$, a note differing widely from any note in the series. In like manner, if other notes are taken as keynotes, and a scale is built up with the order of intervals of the diatonic scale, many more new notes will be needed. This interpolation of notes for both the major and minor scales would increase the number in the octave to seventy-two.

In instruments with fixed keys such a number is unmanageable, and it becomes necessary to reduce the number by changing the value of the intervals. Such a modification of the notes is called *tempering*. Of the several methods proposed by musicians, that of *equal temperament* is the one generally adopted. It makes all the intervals from note to note equal, interpolates one note in each whole tone of the diatonic scale, and thus reduces the number of intervals in the octave to twelve. The only accurately tuned interval in this scale is the octave; all the others are more or less modified. The following table shows the differences between the diatonic and the equally tempered scales:

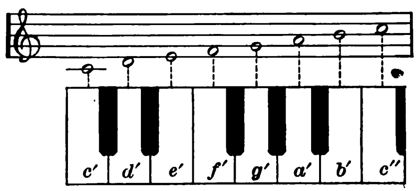


FIGURE 191. — SCALE OF C.

	c′	d′	e′	f′	g′	a′	b′	c″
Diatonic . . .	256	288	320	341.3	384	426.7	480	512
Tempered . . .	256	287.3	322.5	341.7	383.6	430.5	483.3	512

Figure 191 illustrates the scale of *C* on the staff and the keyboard.

226. Limits of Pitch. — The *international pitch*, now in general use in Europe and America, assigns to *a′* the vi-

bration frequency of 435. In the modern piano of seven octaves the bass *A* has a frequency of about 27.5, the highest *A*, 3480.

The lowest note of the organ is the *C* of 16 vibrations per second; the highest note is the same as the highest note of the piano, the third octave above a', with a frequency of 3480.

The limits of hearing far exceed those of music. The range of audible sounds is about eleven octaves, or from the *C* of 16 vibrations to that of 32,768, though many persons of good hearing perceive nothing above a frequency of 16,384, an octave lower.

Questions and Problems

1. Why is the pitch of the sounds given by a phonograph raised by increasing the speed of the cylinder or the disk containing the record?

2. A megaphone or a speaking tube makes a sound louder at a distance. Explain why.

3. The teeth of a circular saw give a note of high pitch when they first strike a plank. Why does the pitch fall when the plank is pushed further against the saw?

4. Miners entombed by a fall of rock or by an explosion have signaled by taps on a pipe or by pounding on the rock. How does the sound reach the surface?

5. Two Rookwood vases in the form of pitchers with slender necks give musical sounds when one blows across their mouth. Why does the larger one give a note of lower pitch than the smaller?

6. What note is made by three times as many vibrations as c' (middle *C*)?

7. If c' is due to 256 vibrations per second, what is the frequency of g'' in the next octave?

8. What is the wave length of g' when sound travels 1130 feet per second?

9. If c' has 264 vibrations per second, how many has a'?

10. When sound travels 1120 ft. per second, the wave length of the note given by a fork was 3.5 ft. What was the pitch of the fork?

IX. VIBRATION OF STRINGS

227. Manner of Vibration. — When strings are used to produce sound, they are fastened at their ends, stretched to the proper tension, and are made to vibrate transversely by drawing a bow across them, striking with a light hammer as in the piano, or plucking with the fingers as in the banjo, guitar, or harp.

228. The Sonometer. — The *sonometer* is an instrument for the study of the laws governing the vibration of

FIGURE 192. — SONOMETER.

strings. It consists of a thin wooden box, across which are stretched violin strings or thin piano wires (Fig. 192). The wires pass over fixed bridges, A and B, near the ends, and are stretched by tension balances at one end. They may be shortened by movable bridges C, sliding along scales under the wires.

229. Laws of Strings. — Stretch two similar wires on the sonometer and tune to unison by varying the tension. Shorten one of them by moving the bridge C to $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, etc. The successive intervals between the notes given by the two wires will be $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, etc. The notes given by the wire of variable length are those of the major diatonic scale. Hence,

The frequency of vibration for a given tension varies inversely as the length.

Starting with a given tension and the strings or wires in unison, increase the stretching force on one of them four times; it will now give the *octave* of the other with twice the frequency. Increase the

tension nine times; it will give the octave plus the fifth, or the *twelfth*, above the other with three times the frequency. These statements may be verified by dividing the comparison wire by a bridge into halves and thirds, so as to put it in unison with the wire of variable tension. Hence,

When the length is constant, the frequency varies as the square root of the tension.

Stretch equally two wires differing in diameter and material, that is, in mass per unit length. Bring them to unison with the movable bridge. The ratio of their lengths will be inversely as that of the square roots of the masses per unit length. Hence,

The length and tension being constant, the frequency varies inversely as the square root of the mass per unit length.

230. Applications. — In the piano, violin, harp, and other stringed instruments, the pitch of each string is determined partly by its length, partly by its tension, and partly by its size or the mass of fine wire wrapped around it. The tuning is done by varying the tension.

231. Fundamental Tone. — Fasten one end of a silk cord about a meter long to one prong of a large tuning fork, and wrap the other end around a wooden pin inserted in an upright bar in such a way that tension can be applied to the cord by turning the pin. Set the fork vibrating, and adjust the tension until the cord vibrates as a whole (Fig. 193). Arranged in this way, the frequency of the fork is double that of the cord.

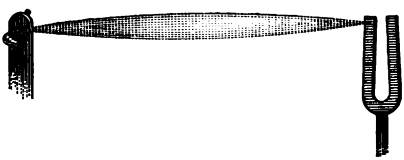


FIGURE 193. — FUNDAMENTAL OF A STRING.

The experiment shows the way a string or wire vibrates when giving its lowest or *fundamental tone.* A body

yields its fundamental tone when vibrating as a whole, or in the smallest number of segments possible.

232. Nodes and Segments. — With a silk cord about 2 m. long, and mounted as in the last experiment, adjust the tension until the cord vibrates in a number of parts, giving the appearance of a succession of spindles of equal length (Fig. 194). The frequency of the fork is twice that of each spindle.

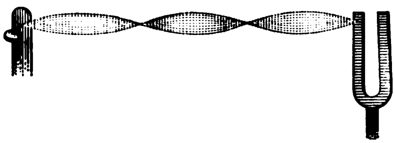


FIGURE 194. — STRING VIBRATING IN SEGMENTS.

Stretch a wire on a sonometer with a thin slip of cork strung on it. Place the cork at one third, one fourth, one fifth, or one sixth part of the wire from one end; touch it lightly, and bow the shorter portion of the wire. The wire will vibrate in equal segments (Fig. 195). The division into segments may be made more conspicuous by placing on the wire, before bowing it, narrow V-shaped pieces of paper, or riders. If, for example, the cork is placed at one fourth

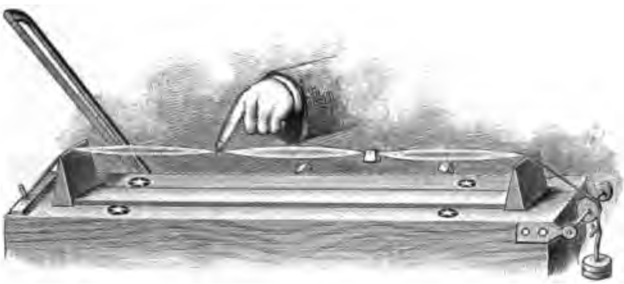


FIGURE 195. — WIRE VIBRATING IN SEGMENTS.

the length of the wire, the paper riders should be in the middle, and at one fourth the length from the other end, and at points midway between these. When the wire is deftly bowed, the riders at the fourths will remain seated, and the intermediate ones will be thrown off. The latter mark points of maximum, and the former those of minimum vibration.

The ends of a wire and the intermediate points of least motion are called *nodes;* the vibrating portions between

the nodes are *loops* or *segments;* and the middle points of the loops are called *antinodes.* The last two experiments illustrate what are known as *stationary waves.* They result from the interference of the direct system of waves and those reflected from the fixed end of the wire. At the nodes the two meet in opposite phase; at the antinodes in the same phase. At the former the motion is reduced to a minimum; at the latter it rises to a maximum.

233. Overtones in Strings. — Stretch two similar wires on the sonometer and tune to unison; then place a movable bridge at the middle of one of them. Set the longer wire in vibration by plucking or bowing it near one end. The tone most distinctly heard is its fundamental. Touch the wire lightly at its middle point; instead of stopping the sound, a tone is now heard in unison with that given by the shorter wire, that is, an octave higher than the fundamental and caused by the longer wire vibrating in halves (Fig. 196). If the wire be again plucked, both the fundamental and the octave may be heard together.

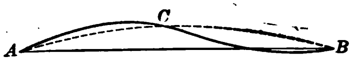


FIGURE 196. — FUNDAMENTAL AND OCTAVE TOGETHER.

Touching the wire one third from the end brings out a tone in unison with that given by the second wire reduced to one third its length by the movable bridge, that is, it yields a tone of three times the frequency, or an octave and a fifth higher than the fundamental. Figure 197 illustrates the manner in which the wire is vibrating.

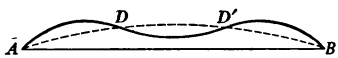


FIGURE 197. — FUNDAMENTAL AND OCTAVE PLUS FIFTH TOGETHER.

The experiment shows that a wire may vibrate not only as a whole but at the same time in parts, yielding a complex note. The tones produced by a body vibrating in parts are called *overtones* or *partial tones.*

234. Harmonics. — If the frequency of vibration of the overtone is an exact multiple of the fundamental, it is called an *harmonic partial* or simply an *harmonic.* In

strings the overtones are usually harmonics, but in vibrating plates and membranes they are not.

The harmonics are named first, second, third, etc., in the order of their vibration frequency. The frequency of any particular harmonic is found by multiplying that of the fundamental by a number one greater than the number of the harmonic. For example, the frequency of the first harmonic of c' of 256 vibrations per second is $256 \times 2 = 512$; that of the second is $256 \times 3 = 768$, etc.

X. VIBRATION OF AIR IN PIPES

235. Air as a Source of Sound. — In the use of the resonator we saw that air may be thrown into vibration when

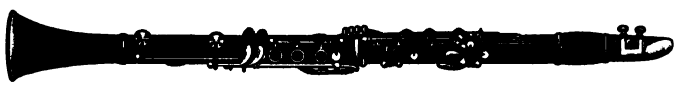


FIGURE 198. — CLARINET.

it is confined in tubes or globes, and that it thus becomes the source of sound. Such a body of air may be set

FIGURE 199. — FLUTE.

vibrating in two ways; by a vibrating tongue or reed, as in the clarinet (Fig. 198), the fish horn, etc., or by a

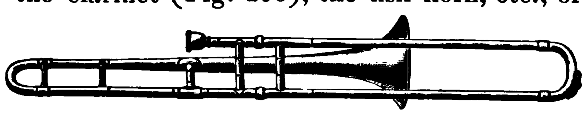


FIGURE 200. — TROMBONE.

stream of air striking against the edge of an opening in the tube, as in the whistle, the flute (Fig. 199), the organ pipe, etc. In several pipe or wind instruments the lips

of the player act as reeds, as in the trumpet, trombone (Fig. 200), the French horn, and the cornet. Wind instruments may be classed as open or stopped pipes, according as the end remote from the mouthpiece is open or closed.

236. Fundamental of a Closed Pipe. — Let the tall jar of Fig. 201 be slowly filled with water until it responds strongly to a c' fork, for example. The length of the column of air will be about 13 in. or one fourth of the wave length of the note.

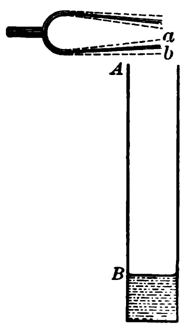


FIGURE 201. — FUNDAMENTAL OF CLOSED PIPE.

When the prong at a moves to b, it makes half a vibration, and generates half a sound wave. It sends a condensed pulse down the tube AB, and this pulse is reflected from the water at the bottom. Now, if AB is one fourth a wave length, the distance down and back is one half a wave length, and the pulse will return to A at the instant when the prong begins to move from b back to a, and to send a rarefaction down AB. This in turn will run down the tube and back, as the prong completes its vibration; the co-vibration is then repeated indefinitely, the tube responds to the fork, and its length is one quarter of the wave length. Hence,

The fundamental of a closed pipe is a note whose wave length is four times the length of the pipe.

237. Laws for Columns of Air. — Set vertically in a wooden base eight glass tubes each about 25 cm. long and 2 cm. in diameter (Fig. 202). Pour in them melted paraffin to close the bottom. A musical note may be produced by blowing a stream of air across the top of each tube. From the confused flutter made by the air striking the edge of the tube, the column of air selects for reënforcement the frequency corresponding to its own rate. Hence the pitch may be varied by pouring in water. Adjust all the tubes with water until they give the eight notes of the major diatonic scale. The measured lengths of the columns of air will be found to be nearly as 1, $\frac{8}{9}$, $\frac{4}{5}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{8}{15}$, $\frac{1}{2}$.

The notes emitted have the frequencies 1, $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$, 2 (§ 224). Hence,

The frequency of a vibrating column of air is inversely as its length.

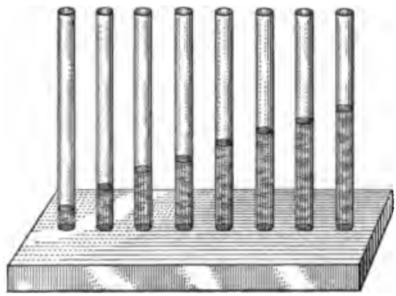


FIGURE 202. — PIPES FOR NOTES OF MAJOR DIATONIC SCALE.

This is the principle employed in playing the trombone.

Blow gently across the end of an open tube 30 cm. long and about 2 cm. in diameter and note the pitch. Take another tube of the same diameter and 15 cm. long; stop one end by pressing it against the palm of the hand, and sound it by blowing across the open end. The pitch of the closed pipe will be the same as that of the open one. The experiment may be varied by comparing the notes obtained by the shorter pipe when open and when closed at one end; the former will be an octave higher than the latter. Hence,

FIGURE 203. — NODE AT MIDDLE OF PIPE.

For the same frequency, the open pipe is twice the length of the stopped one.

The length of the open pipe is, therefore, half the wave length of the fundamental note in air.

238. State of the Air in a Sounding Pipe. — Employing an open organ pipe, preferably with one glass side (Fig. 203), lower into it a miniature tambourine about 3 cm. in diameter and covered with fine sand, while the pipe is sounding its fundamental note. The sand will be agitated most at the ends of the pipe and very little at the middle. There is, therefore, a *node* at the middle of an open pipe. A node is a place of least motion and greatest change of density; an antinode is a place of greatest motion and least change of density. The closed

end of a pipe is necessarily a node, and the open end an antinode. Hence,

In an open pipe, for the fundamental tone, there is a node at the middle and an antinode at each end; in the stopped pipe, there is a node at the closed end and an antinode at the other end.

239. Overtones in Pipes. — Blow across the open end of a glass tube about 75 cm. long and 2 cm. in diameter. A variety of tones of higher pitch than the fundamental may be obtained by varying the force of the stream of air.

These tones of higher pitch than the fundamental are *overtones;* they are caused by the column of air vibrating in parts or segments with intervening nodes.

Open pipes give the complete series of overtones, with frequencies 2, 3, 4, 5, etc. times that of the fundamental.

In stopped pipes only those overtones are possible whose frequencies are 3, 5, 7, etc. times that of the fundamental.

Briefly, the reason is that with a node at one end and an antinode at the other, the column of air can divide into an *odd* number of equal half segments only.

It follows that the notes given by open pipes differ in quality from those of closed pipes.

XI. GRAPHIC AND OPTICAL METHODS

240. Record of Vibrations. — Graphic methods of studying sound are of service in determining the frequency of vibration. Figure 204 shows a practical device for this purpose. A sheet of paper is wrapped around a metal cylinder, and is then smoked with lampblack. A large fork is securely mounted, so that a light style attached to one prong touches the paper lightly. The cylinder is

mounted on an axis, one end of which has a screw thread cut in it, so that when the cylinder turns it also moves in the direction of its axis. The beats of a seconds pendulum may be marked on the paper by means of electric sparks between the style and the cylinder. The number of waves between successive marks made by the spark is equal to the frequency of the fork.

FIGURE 204. — INSCRIBING THE VIBRATIONS OF A FORK.

241. Manometric Flames. — A square box with mirror faces is mounted so as to turn around a vertical axis (Fig. 205). In front of the revolving mirrors is supported a short cylinder *A*, which is divided into two shallow chambers by a partition of goldbeater's skin or thin rubber. Illuminating gas is admitted to the compartment on the right through the tube with a stop-cock, and burns at the small gas jet on the little tube running into this same compartment. The speaking tube is connected to the compartment on the other side of the flexible partition.

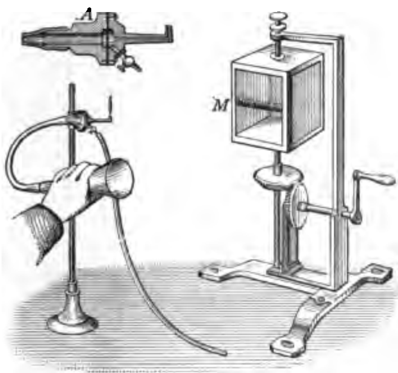


FIGURE 205. — MANOMETRIC FLAME APPARATUS.

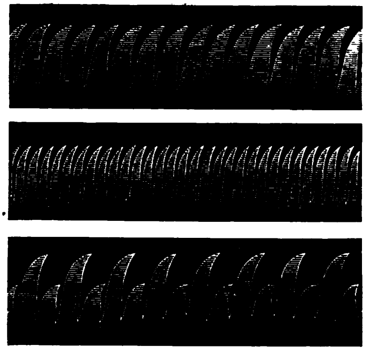


FIGURE 206. — MANOMETRIC FLAMES.

When the mirrors are turned, the image of the gas jet is drawn out into a smooth band of light. Any pure tone at the mouthpiece produces alternate compressions and rarefactions in both chambers separated by the membrane, and these aid and retard the flow of gas to the burner. The flame changes shape and flickers, but its vibrations are too rapid to be seen directly. But if it is examined by reflection from the rotating mirrors, its image is a serrated band (Fig. 206).

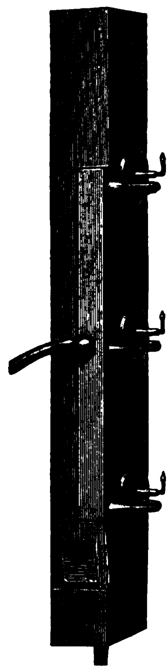


FIGURE 207. — ORGAN PIPE WITH GAS FLAMES.

Koenig fitted three of these little capsules with jets to the side of an open organ pipe (Fig. 207), the membrane on the inner side of the gas chamber forming part of the wall of the pipe. When the pipe is blown so as to sound its fundamental tone, the middle point is a node with the greatest variations of pressure in the pipe, and the flame at that point is more violently agitated than at the other two, giving in the mirrors the top band of Fig. 206. By increasing the air blast, the fundamental is made to give way to the first overtone; the two outside jets then vibrate most strongly, and give the second band in the figure, with twice as many tongues of flame

as in the image for the fundamental. The third band may be obtained by adjusting the air pressure so that both the fundamental and the first overtone are produced at the same time. This same figure may be obtained by singing into the mouthpiece or funnel of Fig. 205 the vowel sound *o* on the note *B*, showing that this vowel sound is composed of a fundamental and its octave.

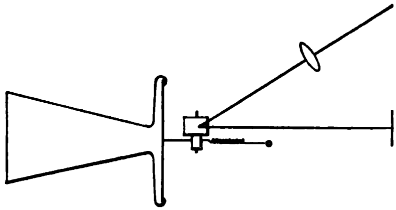


FIGURE 208. — THE PHONODEIK.

242. The Phonodeik is an instrument devised by Professor Dayton C. Miller to exhibit sound waves. It consists of a very small and thin glass mirror mounted on a minute steel spindle resting in jeweled bearings. On this spindle is a little pulley around which wraps a fine thread. One end of the thread is attached to a very thin glass diaphragm closing the small end of a resonator horn; the other is connected to a delicate tension spring (Fig. 208). A small pencil of light is focused on the mirror by a lens and is reflected by the mirror to a sensitized film moving at right angles to it. Any vibration of the diaphragm traces on the film a wave form marked with all the perculiarities of the sound producing the vibrations of the diaphragm. These photographs are afterwards enlarged. Fig. 209 shows the wave form caused by a heavy tuning fork. Fig. 210 represents the wave of

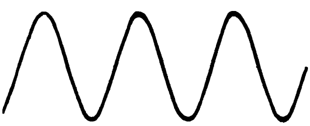


FIGURE 209. — WAVE FORM FROM TUNING FORK.

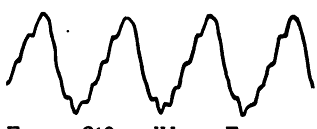


FIGURE 210. — WAVE FORM OF VIOLIN TONE.

FIGURE 211. — WAVE FORM OF VOICE.

a violin tone, the irregularities marking the overtones. Fig. 211 is the wave form of the sound of the human voice saying "ah."

Questions and Problems

1. Name three ways in which musical sounds may differ.

2. Pianos are made so that the hammers strike the wires near one end and not in the middle. Why?

3. Why does the pitch of the sound made by pouring water into a tall cylindrical jar rise as the jar fills?

4. What effect does a rise of temperature have on the pitch of a given organ pipe? Explain.

5. If the pipes of an organ are correctly tuned at a temperature of 40° F., will they still be in tune at 90° F.? Explain.

6. The tones of three bells form a major triad. One of them gives a note *a* of 220 vibrations per second, and its pitch is between those of the other two. What are the frequencies of three bells, and what is the note given by the highest?

7. How much must the tension of a violin string be increased to raise its pitch a fifth (§ 223)?

8. If the *E* string of a violin is 40 cm. long, how long must a similar one be to give *G*?

9. The vibration frequency of two similar wires 100 cm. long is 297. How many beats per second will be given by the two wires when one of them is shortened one centimeter?

10. Two c' forks gave 5 beats per second when one of them was weighted with bits of sealing wax. Find the frequency of the weighted fork.

11. What will be the length of a stopped organ pipe to give c' of 256 vibrations per second when the temperature of the air is 20° C.?

12. Calculate the length of an open organ pipe whose fundamental tone is one of 32 vibrations per second, and the temperature of the air is 20° C.

13. An open organ pipe sounds c' (256); what notes are its two lowest overtones?

14. What is the frequency of an 8-foot stopped pipe when the velocity of sound is 1120 ft. per second?

15. Two open organ pipes 2 ft. in length are blown with air at a temperature of 15° and 20° C., respectively. How many beats do they give per second?

16. When the temperature of the air is such that the velocity of sound is 1105 ft. per second, what will be the frequency of the fundamental note produced by blowing across one end of a tube 12.75 in. long, the other end being closed? What will be the frequency of its first overtone?

CHAPTER VIII

LIGHT

I. NATURE AND TRANSMISSION OF LIGHT

243. The Ether. — Exhaust the air as far as possible from a glass bell jar. Place a candle on the far side of the jar; it will be seen as clearly before the air has been let into the bell jar as after.

It is obvious that the medium conveying light is not the air and it must be something that exists even in a vacuum. This medium is vaguely known as *the ether*. It exists everywhere, even penetrating between the molecules of ordinary matter.

244. Light. — The prevailing view about the nature of light is that it is *a transverse wave motion in the ether*. Huyghens, a Dutch physicist, in 1678 proposed the theory that light is a wave motion; later, Fresnel, a French physicist, showed that the disturbance must be transverse; finally Maxwell modified the theory to the effect that these disturbances are probably *not transverse physical movements of the ether, but transverse alterations in its electrical and magnetic conditions.*

245. Transparent and Opaque Bodies. — When light falls on a body, in general, a part of it is reflected, a part passes through or is transmitted, and the rest is absorbed. A body is *transparent* when it allows light to pass through it with so little loss that objects can be easily distinguished through it, as in the case of clear glass, air, pure water. *Translucent* bodies transmit light, but so imperfectly that

NIAGARA FALLS POWER PLANT.

Used for light and power in several cities of New York State.

objects cannot be seen distinctly through them, as horn, oiled paper, very thin sheets of metal or wood. Other bodies, such as blocks of wood or iron, transmit no light, and these are *opaque*. No sharp line of separation between these classes can be drawn. The degree of transparency or opacity depends on the nature of the body, its thickness, and the wave length (§ 310) of the light. Water when deep enough cuts off all light; the bottom of the deep ocean is dark. Stars invisible at the foot of a mountain are often visible at the top; bodies opaque to light of one wave length are often transparent to light of a different wave length.

246. Speed of Light. — Previous to the year 1676 it was believed that light traveled infinitely fast, because no one had found a way to measure so great a velocity. But in that year Roemer, a young Danish astronomer, made the very important discovery that *light travels with finite speed*. Roemer was engaged at the Paris Observatory in observing the eclipses of the inner moon of the planet Jupiter. At each revolution of the moon M (Fig. 212) in its orbit around the planet J, it passes into the shadow of the planet and becomes invisible from the earth at E, or is eclipsed. By comparing his observations with

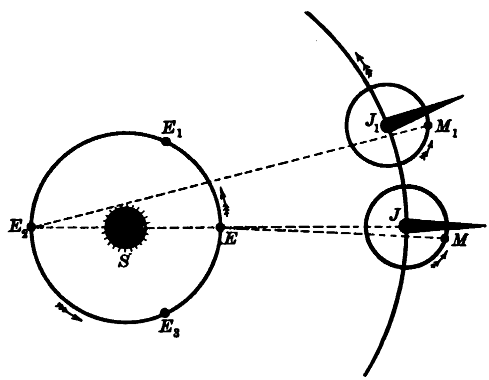


FIGURE 212. — SPEED OF LIGHT FROM JUPITER'S INNER MOON.

much earlier recorded ones, Roemer found that the mean interval of time between two successive eclipses was 42.5 hours. From this it was easy to calculate in advance the time at which succeeding eclipses would occur. But when the earth was going directly away from Jupiter, as at E_1, the eclipse interval was found to be longer than anywhere else; and at E_2, across the earth's orbit from Jupiter, each eclipse occurred about 1000 sec. later than the predicted time. To account for this difference Roemer advanced the theory that this interval of 1000 sec. is the time taken by light to pass across the diameter of the earth's orbit. This gave for the speed of light 309 million meters, or 192,000 miles per second.

Later determinations in our own country by Michelson and Newcomb show that the speed of light is 299,877 km., or 186,337 mi. per second.

247. Direction of Propagation. — Place a sheet-iron cylinder over a strong light, such as a Welsbach gas lamp, in a darkened room. The cylinder should have a small hole opposite the light. Stretch a heavy white thread in the light streaming through the aperture. When the thread is taut it is visible throughout its entire length, but if permitted to sag it becomes invisible.

The experiment shows that *light travels in straight lines.* It will appear later that this is true only when the medium through which light passes has the same physical properties in all directions.

248. Ray, Beam, Pencil. — Light is propagated outward from the luminous source in concentric spherical waves, as sound waves in air from a sonorous body. *Rays are the radii of these spherical waves*, and they are, therefore, normal (perpendicular) to them. They mark the direction of propagation.

When the source of light is at a great distance, the rays

incident on any surface are sensibly parallel. A number of parallel rays form a *beam of light.* For example, in the case of light from the sun or stars, the distance is so great that the rays are sensibly parallel. Rays of light proceeding outward from a point form a *diverging pencil;* rays proceeding toward a point, a *converging pencil.*

249. Shadows. — Place a ball between a lighted lamp and a white screen. From a part of this screen the light will be wholly cut off, and surrounding this area is one from which the light is excluded in part. If three small holes be made in the screen, one where it is darkest, one in the part where it is less dark, and one in the lightest part, it will be found when one looks through them that the flame of the lamp is wholly invisible through the first, a part of it is visible through the second, and the whole flame through the third.

The space behind the opaque object from which the light is excluded is called the *shadow. The figure on the screen is a section of the shadow.* The darkest part of the shadow, called the *umbra,* is caused by the total exclusion of the light by the opaque object; the lighter part, caused by its partial exclusion, is called the *penumbra.*

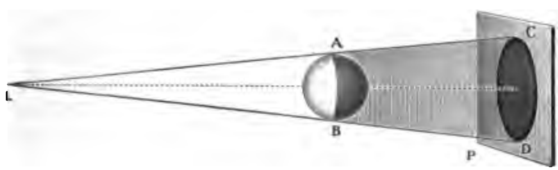


FIGURE 213. — SOURCE OF LIGHT A POINT.

When the source of light is a point L (Fig. 213), the shadow will be bounded by a cone of rays, ALB, tangent to the object, and will have only one part, the umbra. When the source of light is an area, such as LL (Fig. 214), the space $ABDC$ behind the opaque body receives no light, and the parts between AC and AC', and between BD and

BD', receive some light, the amount increasing as AC' and BD' are approached. From these figures the cases when the luminous body is larger than the opaque body,

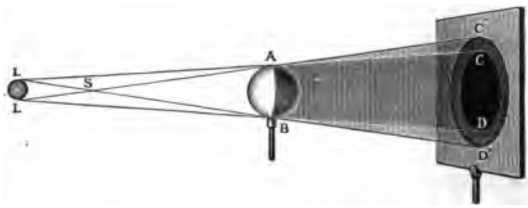


FIGURE 214. — SOURCE OF LIGHT AN AREA.

and when it is of the same size, may be understood and illustrated by the student.

250. Images by Small Openings. — Support two sheets of cardboard (Fig. 215) in vertical and parallel planes. In the center of one cut a hole H about 2mm. square and in front of it place a lighted candle or lamp. An inverted image of the flame will appear on the other sheet if the room is dark. The area of the image will vary with any change in the position of the screen or candle, the brightness with the size of the aperture, but no change in the shape of the aperture affects the image. With a larger aperture the image gains in brightness but loses in definition.

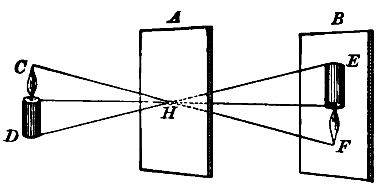


FIGURE 215. — IMAGE BY SMALL OPENING.

Every point of the candle flame is the vertex of a cone of rays, or a diverging pencil, passing through the opening and forming an image of it on the screen. These numerous pictures of the opening overlap and form a picture of the flame, and the number at any one place determines the brightness. The edge of the image will therefore be less bright than other portions. In the case of a large

opening, the overlapping of the images of the aperture destroys all resemblance between the image and the object, the resulting image having the shape of the aperture.

251. Illustrations. — The pinhole camera is an application of the foregoing principle. It consists of a small box, blackened within, and provided with a small opening in one face (Fig. 216); the light passes through this and forms an image on the sensitized plate placed on the oppo-

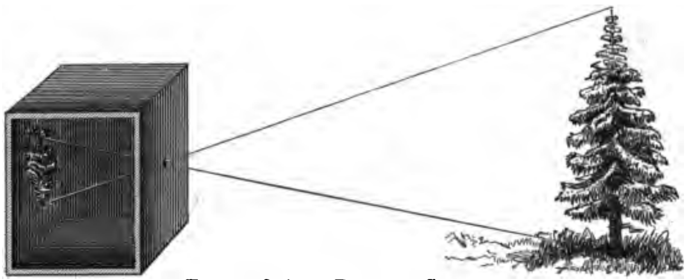


FIGURE 216. — PINHOLE CAMERA.

site side. When the sun shines through the small chinks in the foliage of a tree, a number of round or oval spots of light may be seen on the ground. These are images of the sun. During a partial solar eclipse such figures assume a crescent shape.

II. PHOTOMETRY

252. Law of Intensity. — *The intensity of illumination is the quantity of light received on a unit of surface.* Everyday experience shows that it varies, not only with the source of the light, but also with the distance at which the source is placed.

Cut three cardboard squares, 4, 8, and 12 cm. on a side respectively, and mount them on supports (Fig. 217). The centers of these screens should be at the same distance above the table as the source of light.

Use a Welsbach gas lamp with an opaque chimney having a small opening opposite the center of the light, and set it 99 cm. from the largest screen. Place the medium-sized screen so that it exactly cuts off the light from the edges of the largest. In like manner place the smallest screen with respect to the intermediate one. If these screens are placed with care, it will be found that their distances from the light are 33, 66, and 99 cm. respectively, or as 1 : 2 : 3. Now as each screen exactly cuts off the light from the one next farther away, it

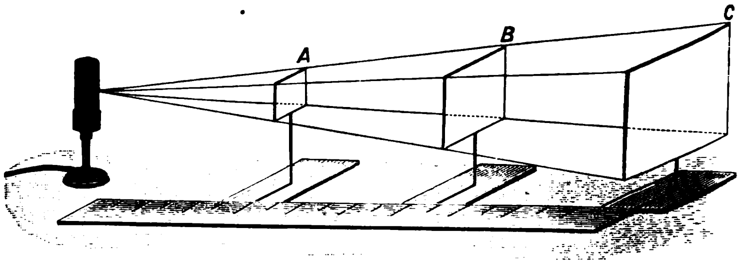


FIGURE 217. — LAW OF INTENSITY OF ILLUMINATION.

follows that each receives the same amount of light from the source when the light is not intercepted. The surfaces of the screens are as 1 : 4 : 9, and hence the quantity of light per unit of surface must be inversely as 1 : 4 : 9, the square of 1, 2, and 3 respectively.

This experiment shows that *the intensity of illumination varies inversely as the square of the distance from the source of light.* If the medium is such as to absorb some of the light, the decrease in intensity is greater than that expressed by the law of inverse squares.

This law of illumination assumes that the source of light is a point, and that the receiving surface is at right angles to the direction of the rays. When the surface on which the light (and heat) falls is inclined, the intensity is still less. In northern latitudes the earth is nearer the sun in winter than in summer, but the intensity of the radiation received is less than in summer, because the alti-

tude of the sun at noon is less, that is, because the earth's surface is more inclined to the direction of the radiations.

253. The Bunsen Photometer. — *A photometer is an instrument for comparing the intensity of one light with that of another.* The principle applied is a consequence of the law of the intensity of illumination; it is that the ratio of the intensities of two lights is equal to the square of the ratio of the distances at which they give equal illumination.

In the Bunsen photometer a screen of paper A (Fig. 218), having a translucent spot made by applying a little

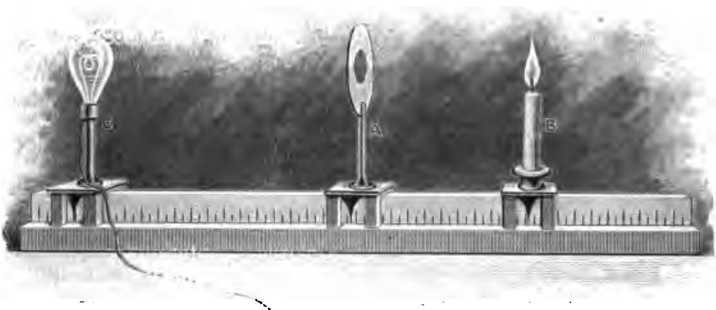


FIGURE 218. — BUNSEN PHOTOMETER.

hot paraffin, is supported on a graduated bar between a standard candle B and the light C to be compared with it. An old but imperfect standard candle is the light emitted by the sperm candle of the size known as "sixes," when burning 120 grains per hour. The photometer screen is usually inclosed in a box open toward the two lights, and back of it are two mirrors placed with their reflecting sides toward each other in the form of a V, so that the observer standing by the side of A can see both sides of the screen by reflection in the mirrors. The

position of A or of B may then be adjusted until both sides of the screen look alike. Then the intensity of C is to the intensity of B as $\overline{AC}^2$ is to $\overline{AB}^2$.

In the Joly photometer two rectangular blocks of paraffin, separated by a sheet of tinfoil, take the place of the sheet of paper. When the lights are balanced the edges of the paraffin blocks are equally lighted.

Questions and Problems

1. What is the cause of an eclipse of the sun? Explain by diagram.

2. What is the cause of an eclipse of the moon? Explain by diagram.

3. Why does a small aperture in the camera give a more sharply defined image than a large one?

4. Why is a larger aperture in the camera necessary for a snapshot than for a time exposure?

5. In an attempt to determine the height of a tree the following data were obtained: Length of the tree's shadow, 50 ft.; length of the shadow of a vertical 10-ft. pole, 4 ft. What is the height of the tree?

6. Two lights, 25 and 100 c.p. respectively, are placed 60 ft. apart. Where must a screen be placed between them and on the line joining them so as to be equally illuminated on its two sides?

7. In measuring the candle power of a lamp the following data were obtained: Distance of the standard lamp from the photometer disk, 20 cm.; distance of lamp, 120 cm. What is the candle power?

8. If a book can be read at a distance of 1 ft. from a 20 c.p. electric lamp, at what distance from a 60 c.p. lamp can it be read with equal clearness?

9. The picture of a tree taken with a pinhole camera was 10 cm. long. The aperture was 20 cm. from the sensitive plate and 30 m. from the tree. What is the height of the tree?

10. Two Mazda lamps are to be used to give equal illumination to the two sides of a screen. One of them is 20 c.p. and distant 8 ft. from the screen; the other is 40 c.p. How far from the screen must the second lamp be placed to secure the desired illumination?

11. What is the length of the umbra of the earth's shadow, the diameter of the earth and sun being 8000 and 880,000 miles respectively, and the distance from the center of the earth to that of the sun being 93,000,000 miles?

III. REFLECTION OF LIGHT

254. Regular Reflection. — When a beam of light falls on a polished plane surface, the greater part of it is reflected in a definite direction. This reflection is known as *regular reflection.* In Fig. 219 a beam of light *IB* is incident on the plane mirror *B* and is reflected as *BR*. *IB* is the *incident beam*, *BR* is the *reflected beam*, the angle *IBP* between the incident beam and the normal (perpendicular) to the reflecting surface is the *angle of incidence*, and the angle *PBR* between the reflected beam and the normal is the *angle of reflection.*

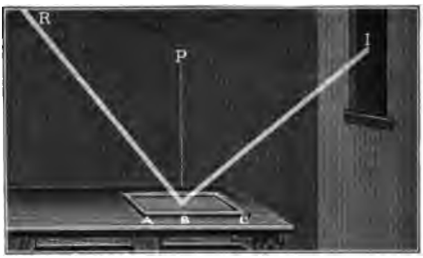


FIGURE 219. — INCIDENCE AND REFLECTION.

255. Law of Reflection. — On a semicircular board are mounted two arms, pivoted at the center of the arc (Fig. 220). One arm carries a vertical rod *P*, and the other a paper tube *T* with parallel threads stretched across a diameter at each end. A plane mirror *M* is mounted at the center of the semicircle, with its reflecting surface parallel to the diameter at the ends of the arc. On the

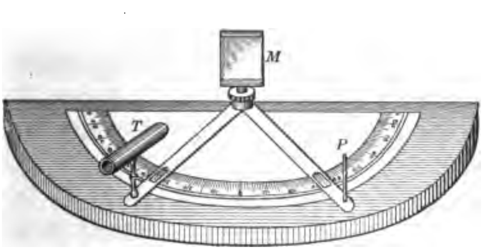


FIGURE 220. — LAW OF REFLECTION.

edge of the semicircle is a scale of equal parts with the zero on the normal to the mirror. Place the arm P in any desired position and move the arm T until the image of the rod in the mirror is exactly in line with the two threads. The scale readings will show that the two arms make equal angles with the normal to the mirror. Hence,

The angle of reflection is equal to the angle of incidence; and the incident ray, the normal, and the reflected ray all lie in the same plane.

256. Diffused Reflection. — Cover a large glass jar with a piece of cardboard, in which is a hole about 1 cm. in diameter. Fill the jar with smoke, and reflect into it through the hole in the cover a beam of sunlight. The whole of the interior of the jar will be illuminated.

The small particles of smoke floating in the jar furnish a great many reflecting surfaces; the light falling on them is reflected in as many directions. The scattering of light by uneven or irregular surfaces is *diffused reflection.*

To a greater or less extent all reflecting surfaces scatter light in the same way as the smoke particles. Figure 221 illustrates in an exaggerated way the difference between a perfectly smooth surface and one somewhat uneven.

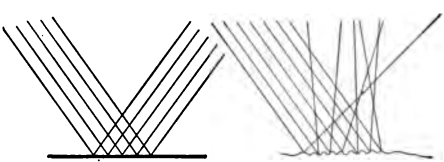


FIGURE 221. — REGULAR AND DIFFUSED REFLECTION.

It is by diffused reflection that objects become visible to us. Perfect reflectors would be invisible; it is almost impossible to see the glass of a very perfectly polished mirror. The trees, the ground, the grass, and particles floating in the air reflect the light from the sun in every direction, and thus fill the space about us with light. If the air were free from all floating particles and gases, the sky would be dark in all

directions, except in the direction of the sun and the stars. This conclusion is confirmed by aëronauts who have reached very high altitudes, where there was almost a complete absence of floating particles.

257. Image in a Plane Mirror. — Any smooth reflecting surface is called a *mirror*. A *plane mirror* is one whose reflecting surface is a plane. A *spherical mirror* is one whose reflecting surface is a portion of a sphere.

Support a pane of clear window glass in a vertical position, and place a red-colored lighted candle back of it. Place a white unlighted candle in front. Move the unlighted candle until its image in the glass as a mirror coincides exactly with the lighted candle seen through the glass. The distance of the two candles from the mirror will be the same.

Let A be a luminous point in front of a plane mirror MN (Fig. 222). The group of waves included between the rays AB and AC after reflection proceed as if from A', situated on the normal AK and as far behind the reflecting surface as A is in front of it. An eye placed at DE receives these waves as if they came directly from a source A'. The point A' is called the image of A in the mirror MN. It is known as a *virtual image*, because the light only appears to come from it. Therefore, *the image of a point in a plane mirror is virtual, and is as far back of the mirror as the point is in front.* The image may be found by drawing

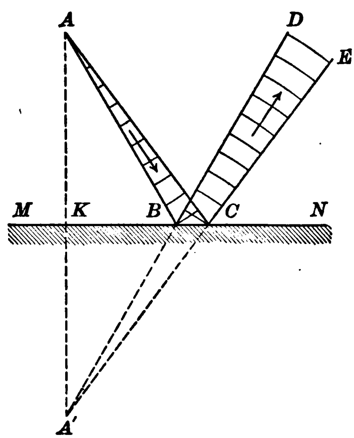


FIGURE 222. — POSITION OF IMAGE OF A POINT.

from the point a perpendicular to the mirror, and producing the perpendicular until its length is doubled.

258. Construction for an Image in a Plane Mirror. — As the image of an object is composed of the images of its points, the image may be located by finding those of its points. Let *AB* (Fig. 223) represent an object in front of the plane mirror *MN*. Draw perpendiculars from *A* and *B* to the mirror and produce them until their length is doubled. *A'B'* is the image of *AB*. It is virtual, erect, and of the same size as the object.

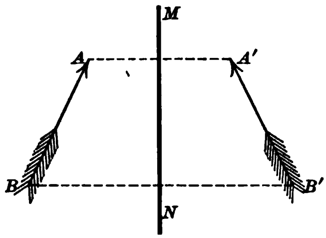


FIGURE 223. — CONSTRUCTION OF IMAGE.

An image in a plane mirror is reversed from right to left. This is clearly seen when a printed page is held in front of a mirror, the letters all being reversed, or *perverted*, as it is termed. Otherwise the image is so like the object that illusions are produced, because a well-polished mirror itself is invisible.

In general, *the image in a plane mirror is the same size as the object, is virtual, and is as far back of the mirror as the object is in front.*

259. Path of the Rays to the Eye. — It is important to notice that the image of any fixed object is fixed in space, and is entirely independent of the position of the observer. The paths of the rays for the image for one observer are not the same as those for another.

Let *AB* (Fig. 224) represent an object in front of the plane mirror *MN*. Drop perpendiculars from points of the object to the mirror, and produce them until their length is doubled. In this manner the image of *AB* is found at *A'B'*. Let *E* and *E'* be the position of the eye

for two observers. To find the path of the rays entering the eye at E, draw lines from A' and B' to E. These lines are the directions in which the light enters the eye from A' and B' respectively. But no light comes from behind the mirror, and so the intersections of these lines with the mirror are the points where the rays from A and B are reflected to E. In a similar manner the path of the rays may be traced for the position of the eye at E'. The full lines in front of the mirror are the paths of the rays from A and B, which give the images at A' and B'.

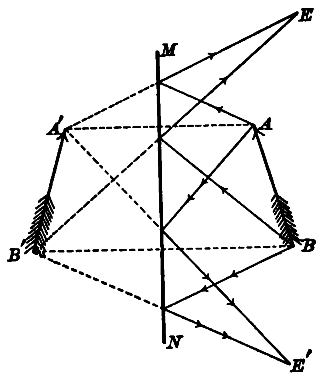


FIGURE 224. — PATH OF RAYS TO THE EYE.

260. Uses of a Plane Mirror. — The employment of the plane mirror as a "looking glass" dates from a period of great antiquity. The process of covering a glass surface with an amalgam of tin and mercury came into use in Venice about three centuries ago. The process of covering glass with a film of silver was invented during the last century.

The fact that the image in a plane mirror is virtual has been used to produce many optical illusions, such as the stage ghost, the magic cabinet, the decapitated head, etc. To produce the illusion of a ghost, a large sheet of unsilvered plate glass, with its edges hidden by curtains, is so placed that the audience has to look obliquely through it to see the actors on the stage. Other actors, hidden from direct view, and strongly illuminated, are seen by reflection in the glass as ghostly images on the stage.

261. Multiple Reflection. — Place two mirrors so that their reflecting surfaces form an angle (Fig. 225). If a lighted candle be placed between them, several images may be seen in the mirrors; three when they are at right angles, more when the angle is less than a right angle. When the mirrors are parallel, all the images are in a straight line perpendicular to the mirrors.

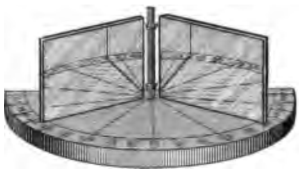


FIGURE 225. — MULTIPLE REFLECTION.

The image in one mirror serves as an object for the second mirror, and the image in the second becomes in turn an object for the first mirror. In Fig. 226 the two mirrors are at right angles. O' is the image of O in AB, and is found as in § 258. O''' is the image of O' in AC, and is found by the line $O'O'''$ drawn perpendicular to AC produced. O'' is the image of O in AC, and since the mirrors are at right angles, O''' is also the image of O'' in AB. O''' is situated behind the plane of both mirrors, and no images of it can be formed. All the images are situated in the circumference of a circle whose center is A and radius AO. If E is the position of the eye, then O' and O'' are each seen by one reflection, and O''' by two reflections, and for this reason it is less bright. To trace the path of a ray for the image O''', draw $O'''E$, cutting AB at b, and from the intersection b draw bO'', cutting AC at a. Join aO; the path of the ray is $OabE$. It is interesting to find the images when the mirrors are at various angles.

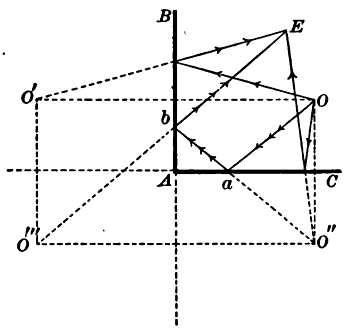


FIGURE 226. — MIRRORS AT RIGHT ANGLES.

262. Illustrations. — The double image of a bright star and the several images of a gas jet in a thick mirror (Fig. 227) are examples of multiple reflection, the front surface of the mirror and the metallic surface at the back serving as parallel reflectors. Geometrically the number of images is infinite; but on account of their faintness only a limited number is visible. The *kaleidoscope*, a toy invented by Sir David Brewster, is an interesting application of the same principle. It consists of a tube containing three mirrors extending its entire length, the angle between any two of them being 60°. One end of the tube is closed by ground glass, and the other by a cap with a round hole in it. Pieces of colored glass are placed loosely between the ground glass and a plate of clear glass parallel to it. On looking through the hole at any source of light, multiple images of these pieces of glass are seen, symmetrically arranged around the center, and forming beautiful figures, which vary in pattern with every change in the position of the pieces of glass.

FIGURE 227. — MULTIPLE IMAGES.

263. Spherical Mirrors. — A mirror is *spherical* when its reflecting surface is a portion of the surface of a sphere. If the inner surface is polished for reflection, the mirror is *concave;* if the outer surface, it is *convex.* Only a small portion of a spherical surface is used as a mirror. In Fig. 228 the *center C* of the mirror *MN* is the center of curvature of the sphere of which the reflecting surface is a part. The middle point *A* of the

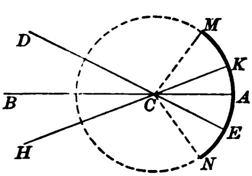


FIGURE 228. — SPHERICAL MIRROR.

reflecting surface MN is the *pole* or *vertex* of the mirror, and the straight line AB passing through the center of curvature C and the pole A of the mirror is its *principal axis*. Any other straight line through the center and intersecting the mirror is a *secondary axis*. The figures of spherical mirrors in this chapter are sections of a sphere made by passing a plane through the principal axis.

The difference between a plane mirror and a spherical one is that the normals to a plane mirror are all parallel lines, while those of a spherical mirror are the radii of the surface, and all pass through the center of curvature.

264. Principal Focus of Spherical Mirrors. — A *focus* is the point common to the paths of all the rays after incidence. It is a *real* focus if the rays of light actually pass through the point, and *virtual* if they only appear to do so.

Let the rays of the sun fall on a concave spherical mirror. Hold a graduated ruler in the position of its principal axis, and slide along it a small strip of cardboard. Find the point where the image of the sun is smallest. This will mark the principal focus, and it is a real one. If a convex spherical mirror be used the light will be reflected as a broad pencil diverging from a point back of the mirror. The focus is then a virtual one.

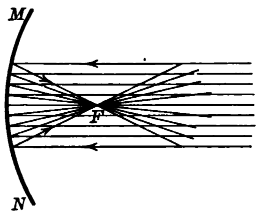


FIGURE 229. — PRINCIPAL FOCUS, CONCAVE MIRROR.

If a pencil of rays parallel to the principal axis falls on a concave spherical mirror, the point to which the rays converge after reflection is called the *principal focus* of the mirror (Fig. 229). In the case of a convex spherical mirror, the principal focus is the point on the axis behind the mirror from which the reflected rays diverge (Fig. 230). The dis-

tance of the principal focus from the mirror is its *principal focal length.*

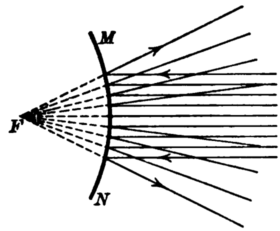


FIGURE 230. — PRINCIPAL FOCUS, CONVEX MIRROR.

265. Position of the Principal Focus. — Let *MN* (Fig. 231) be a concave mirror whose center is at *C* and principal axis is *AB*. Let *ED* be a ray parallel to *BA*. Then *CD* is the normal at *D*; and *CDF*, the angle of reflection, must equal *EDC*, the angle of incidence. Since the ray *BA* is normal to the mirror, it will be reflected back along *AB*. The reflected rays *DF* and *AB* have a common point *F*, which is the principal focus. The triangle *CFD* is isosceles with the sides *CF* and *FD* equal. (Why?) But when the point *D* is near *A*, *FD* is equal to *FA*; *F* is therefore the middle point of the radius *CA*. Other rays parallel to *BA* will pass after reflection nearly through *F*. Hence, *the principal focus of a concave spherical mirror is real and is halfway between the center of curvature and the vertex.*

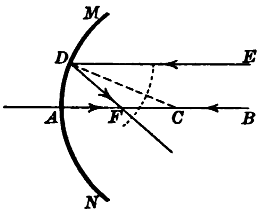


FIGURE 231. — POSITION OF PRINCIPAL FOCUS.

Let *MN* (Fig. 232) be a convex spherical mirror. *ED* and *BA* are rays parallel to the principal axis. When produced back of the mirror, after reflection, their common point *F* is back of the mirror and halfway between *A* and *C*. (Why?) Hence, *the princi-*

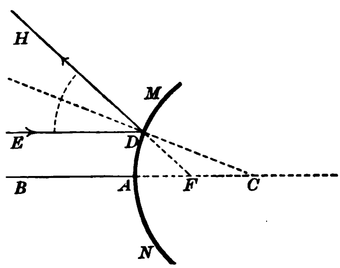


FIGURE 232. — PRINCIPAL FOCUS VIRTUAL FOR CONVEX MIRROR.

pal focus of a convex spherical mirror is virtual and halfway between the center of curvature and the mirror.

266. Conjugate Foci of Mirrors. — When a diverging pencil of light ABD (Fig. 233) falls on the spherical mirror MN, it is focused after reflection at a point B' on the axis AB which passes through the radiant point or source of light; after reflection the rays diverge from this focus B' as a new radiant point. When rays diverging from one point converge to another, the two points are called *conjugate foci*.

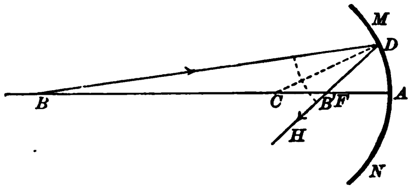


FIGURE 233. — CONJUGATE FOCI, CONCAVE MIRROR.

In Fig. 234, the rays BA and BD diverge from B as the radiant point; after reflection they diverge as if they came from B' behind the reflecting surface; B' is a virtual focus and B and B' are conjugate foci.

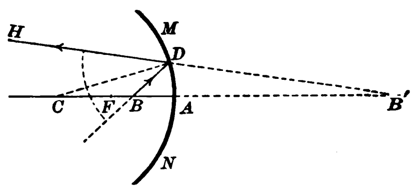


FIGURE 234. — CONJUGATE FOCI, ONE FOCUS VIRTUAL.

In the first case the source of light is farther from the mirror than the center of curvature, and the focus is real; in the second case it is nearer the mirror than the principal focus, and the focus is virtual.[1]

[1] In Fig. 233, CD bisects the angle BDH. Hence, $\frac{BD}{B'D} = \frac{BC}{B'C}$. If D is close to A, we may, without sensible error, place $BD = BA$ and $B'D = B'A$. Put $BA = p$, $B'A = q$, $CA = r = 2f$. Then $BC = p - r$, $B'C = r - q$, and $\frac{p}{q} = \frac{p-r}{r-q}$, from which $\frac{1}{p} + \frac{1}{q} = \frac{2}{r} = \frac{1}{f}$. By measuring p

267. Images in Spherical Mirrors. — In a darkened room support on the table a concave spherical mirror, a candle, and a small white screen. Place the candle anywhere beyond the focus, and move the screen until a clear image of the flame is formed on it (Fig. 235). Notice the size and position of the image, and whether it is erect or inverted. When the candle is between the focus and the mirror, an image of it cannot be obtained on the screen, but it can be seen by looking into the mirror. The same is true for the convex mirror, whatever be the position of the candle; in these last cases the image is a virtual one.

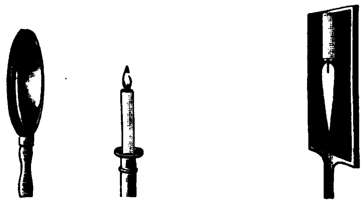


FIGURE 235. — IMAGE BY CONCAVE MIRROR.

The experiment shows the relative positions of the object and its image for a concave mirror, all depending on the position of the object with respect to the mirror. If these positions are carefully noted it will be seen that there are six distinct cases as follows:

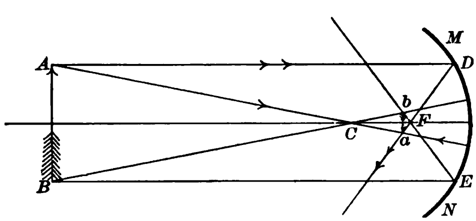


FIGURE 236. — OBJECT BEYOND CENTER OF CURVATURE.

First. — When the object (*AB*, Fig. 236) is at a finite distance beyond the center of curvature, the image is real, inverted, smaller than the object, and between the center of curvature and the principal focus.

Second. — When a small object is at the center of curvature, the image is real, inverted, of the same size as the

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and q, we may compute r and f. For the convex mirror, q and r are negative.

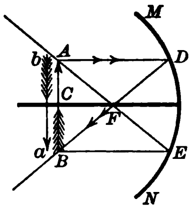


FIGURE 237.—OBJECT AT CENTER OF CURVATURE.

object, and at the center of curvature (Fig. 237).

Third. — When the object is between the center and the principal focus, the image is real, inverted, larger than the object, and is beyond the center (Fig. 238). This is the converse of Case I.

Fourth. — When the object is at the principal focus, the rays are reflected parallel and no distinct image is formed (Fig. 239).

Fifth. — When the object is between the principal focus and the mirror, the image is virtual, erect, and larger than the object (Fig. 240).

Sixth. — When the mirror is convex, the image is always virtual, erect, and smaller than the object (Fig. 241).

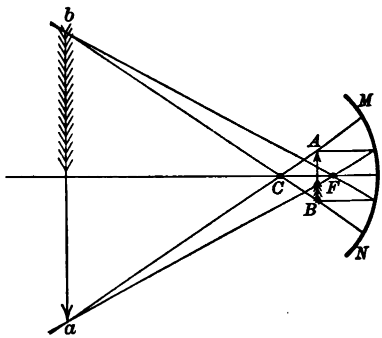


FIGURE 238. — OBJECT BETWEEN CENTER AND PRINCIPAL FOCUS.

268. Construction for Images. — To find images in spherical mirrors by geometrical construction, it is only necessary to find conjugate focal points. To do this trace two rays for each point for the object, one along the secondary axis through it, and the other parallel to the principal axis. The first ray is reflected back on itself, and the second through the

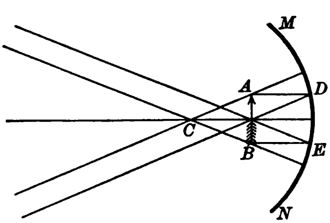


FIGURE 239. — OBJECT AT PRINCIPAL FOCUS.

principal focus. The intersection of the two reflected rays from the same point of the object locates the image of that point.

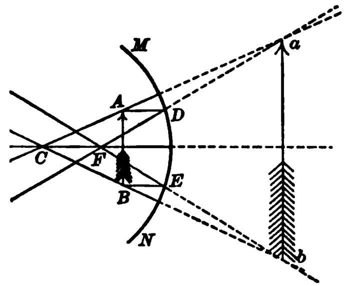


FIGURE 240. — OBJECT BETWEEN PRINCIPAL FOCUS AND MIRROR.

For instance: In Fig. 236, *AC* is the path of both the incident and the reflected ray, while the ray *AD* is reflected through the principal focus *F*. Their intersection is at *a*. The rays *BC* and *BE* are reflected similarly through *b*. Hence, *ab* is the image of *AB*. In Fig. 240, the ray *AC* along the secondary axis, and *AD* reflected back through *F* as *DF*, must be produced to meet back of the mirror at the virtual focus *a*. *A* and *a* are conjugate foci; also *B* and *b*, and *ab* is a virtual image.

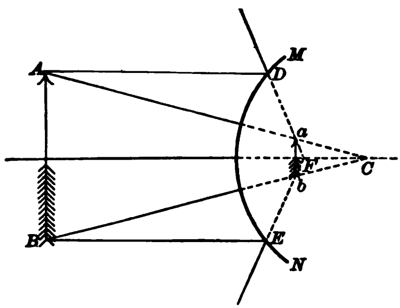


FIGURE 241. — IMAGE ALWAYS VIRTUAL IN CONVEX MIRROR.

For the convex mirror (Fig. 241) the construction is the same. From the point *A* draw *AC* along the normal or secondary axis, and *AD* parallel to the principal axis. The latter is reflected so that its direction passes through *F*. The intersection of these two lines is at *a*. The image *ab* is virtual and erect.

269. Spherical Aberration in Mirrors. — Bend a strip of bright tin into as true a semicircle as possible and fasten it to a vertical board as in Fig. 242. At right angles to the board at one end place

a vertical sheet of cardboard containing three parallel slots. Send a strong beam of light through each of these slots; the three beams will be reflected by the curved tin through different points, the beam nearest the straight rim of the mirror crossing the axis nearest the mirror.

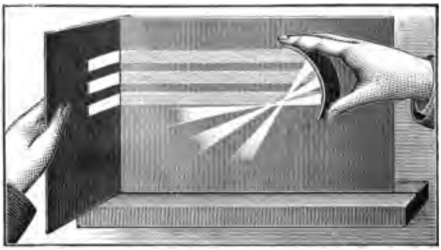


FIGURE 242. — SPHERICAL ABERRATION.

The experiment shows that rays incident near the margin of a spherical mirror cross the axis after reflection between the principal focus and the mirror. This spreading out of the focus is known as *spherical aberration by reflection.* It causes a lack of sharpness in the outline of images formed by spherical mirrors. It is reduced by decreasing the aperture of the mirror by means of a diaphragm to cut off marginal rays, or by decreasing the curvature of the mirror from the vertex outward. The result then is a parabolic mirror (Fig. 243), which finds use in searchlights, lighthouses, headlights of locomotives and automobiles, and in reflecting telescopes.

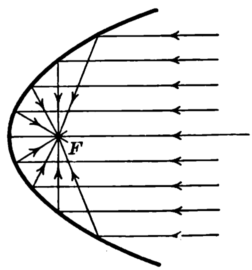
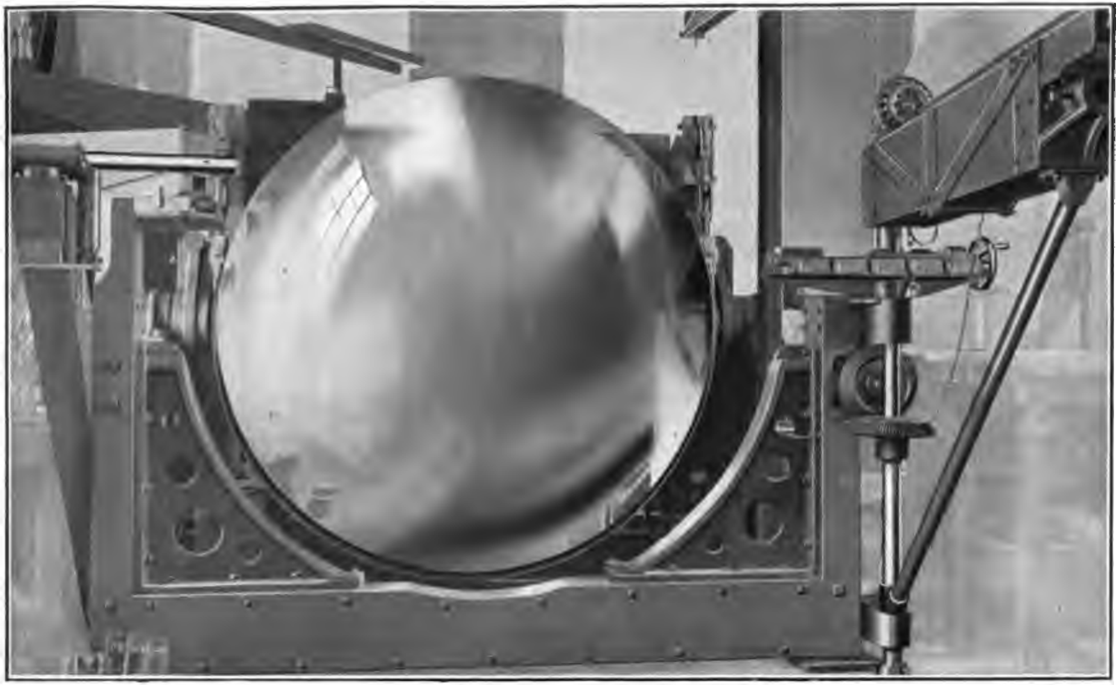


FIGURE 243. — PARABOLIC MIRROR.

270. Caustics by Reflection. — Use the tin reflector of the last experiment as shown in Fig. 244. The light from a candle or a lamp is focused on a curved line.

The curve formed by the rays reflected from a spherical mirror is called the *caustic by reflection.* It may be seen



The 100-Inch Silvered Parabolic Mirror of the Mt. Wilson Solar Observatory.

It is 14 inches thick and weighs $4\frac{1}{2}$ tons. Its focal length is about 50 feet.

by letting sunlight fall on a tin milk pail partly full of milk, or on a plain gold ring on a white surface.

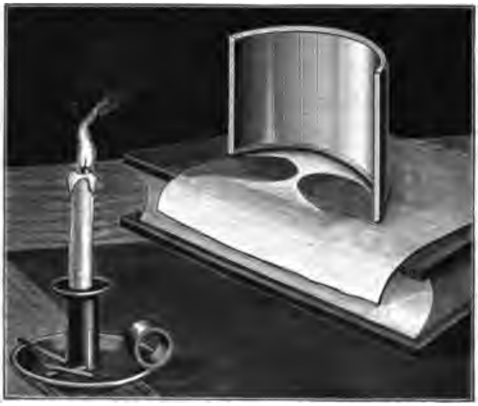


FIGURE 244. — CAUSTIC BY REFLECTION.

Questions and Problems

1. Why is the image of an object seen in the bowl of a silver spoon distorted?

2. Show by an arrangement of plane mirrors how to see around an obstruction.

3. How can a concave, a convex, and a plane mirror be distinguished from one another, even when their outer surfaces are flat, as is often the case?

4. Construct all the images that would be formed of a luminous point placed between two mirrors forming an angle of 60°.

5. Show by a diagram that a person can see his whole length in a short plane mirror placed on a vertical wall by tipping the top of the mirror forward and standing close to the mirror.

6. A candle foot is the intensity of illumination of a 1 c.p. light at a distance of one foot from the illuminated surface. What will be the illumination in foot candles of a surface 10 ft. away from a 50 c.p. lamp?

7. How far must a surface be from a 40 c.p. lamp to receive the same illumination as it would receive from a 4 c.p. lamp two feet distant?

8. If a person can just see to read a book when 10 ft. away from a 16 c.p. lamp, how far away from a 1600 c.p. arc light can he see to read the book?

9. Where must a 16 c.p. lamp be placed between two parallel walls of a room 20 ft. apart in order that one wall may be four times as strongly illuminated as the other?

10. A gas burner consuming 5 cu. ft. per hour gives a flame of 16 c.p. A 16 c.p. electric bulb consumes 44 watts per hour. With gas at $1 per 1000 cu. ft. and electricity at 12½ cents per K. W. hour, which is the cheaper?

11. If an object is 18 ft. distant from a concave spherical mirror and the image formed of it is 2 ft. from the mirror, what is its focal length?

12. Find by a diagram what effect it has on the image of an object in a concave spherical mirror to vary the distance of the object from the mirror.

13. The mirror formula applies equally well to the convex spherical mirror if q, r, and f are made negative. Find the position of the image of an object as given by a convex spherical mirror when the radius of curvature is 20 inches, the object being 10 ft. from the mirror.

14. If a plane mirror is moved parallel to itself directly away from an object in front of it, show that the image moves twice as fast as the mirror.

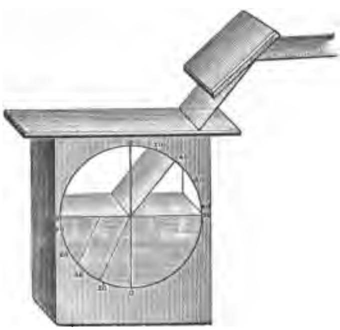


FIGURE 245. — REFRACTION OF LIGHT.

IV. REFRACTION OF LIGHT

271. Refraction. — Fasten a paper protractor scale centrally on one face of a rectangular battery jar (Fig. 245), and fill the jar with water to the horizontal diameter of the scale. Place a slotted cardboard over the top. With

a plane mirror reflect a beam of light through the slit into the jar, at such an angle that the beam is incident on the water exactly back of the center of the scale. The path of this ribbon of light may be traced; its direction is changed at the surface of the water.

The change in the course of light in passing from one transparent medium into another is called *refraction*.

Place a coin at the bottom of an empty cup standing on a table, and let an observer move back until the coin just passes out of sight below the edge of the cup; now pour water into the cup, and the coin will come into view (Fig. 246).

FIGURE 246. — CUP OF WATER AND COIN.

The changes in the apparent depth of a pond or a stream, as the observer moves away from it, are caused by refraction. The broken appearance of a straight pole thrust obliquely into water is accounted for by the change in direction which the rays coming from the part under water suffer as they emerge into the air.

272. Cause of Refraction. — Foucault in France and Michelson in America have measured the velocity of light in water, and have found that it is only three-fourths as great as in air. The velocity of light in all transparent liquids and solids is less than in air, while the velocity in air is practically the same as in a vacuum.

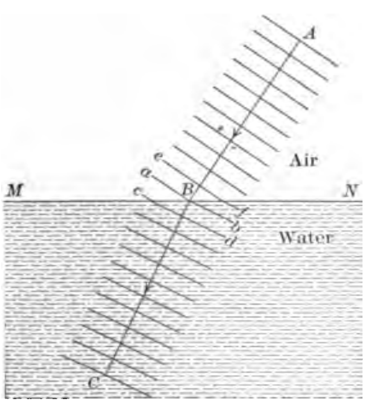


FIGURE 247. — REFRACTION EXPLAINED.

If now a beam of light

is incident obliquely on the surface MN of water (Fig. 247), all parts of a light wave do not enter the water at the same time. Let the parallel lines perpendicular to AB represent short portions of plane waves. Then one part of a wave, as f, will reach the water before the other part, as e, and will travel less rapidly in the water than in the air. The result is that each wave is swung around, that is, the direction of propagation BC, which is perpendicular to the wave fronts, is changed; in other words, the beam is refracted. The refraction of light is, therefore, due to its change in velocity in passing from one transparent medium to another.

273. The Index of Refraction. — Let a beam of light pass obliquely from air to water or glass, and let AB (Fig. 248) be the incident wave front. From A as a center and with a radius AD equal to the distance the light travels in the second medium while it is going from B to C in air, draw the dotted arc. This limits the distance to which the disturbance spreads in the second medium. Then from C draw CD tangent to this arc and draw AD to the point of tangency. CD is the new wave front.

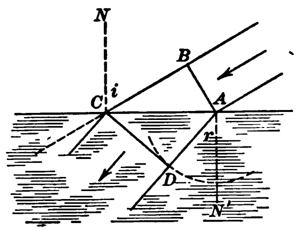


FIGURE 248. — INDEX OF REFRACTION.

The distances BC and AD are traversed by the light in the same time. They are therefore proportional to the velocities of light in the two media. Then the

$$\textit{Index of refraction} = \frac{\textit{speed of light in air}}{\textit{speed in second medium}} = \frac{v}{v'}.$$[1]

[1] The older mathematical definition of the index of refraction is the ratio of the sine of the angle of incidence to the sine of the angle of re-

The angle NCB is the *angle of incidence.* It is equal to the angle BAC between the incident wave front and the surface of separation of the two media. The *angle of refraction* is the angle $N'AD$. It is equal to the angle ACD between the wave front in the second medium and the surface of separation. The angle at C, between the direction of the incident ray and the refracted ray, is the *angle of deviation.*

The following are the indices of refraction for a few substances:

Water	1.33	Crown glass . .	1.51
Alcohol	1.36	Flint glass	1.54 to 1.71
Carbon bisulphide	1.64	Diamond	2.47

For most purposes the index of refraction for water may be taken as $\frac{4}{3}$, for crown glass $\frac{3}{2}$, for flint glass $\frac{13}{8}$, and for diamond $\frac{5}{2}$.

274. Laws of Refraction. — The following laws, which summarize the facts relative to single refraction, were discovered by Snell, a Dutch physicist, in 1621:

I. *When a pencil of light passes obliquely from a less highly to a more highly refractive medium, it is bent toward the normal; when it passes in the reverse direction, it is bent from the normal.*

II. *Whatever the angle of incidence, the index of refraction is a constant for the same two media.*

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fraction. Now the sine of an angle in a right triangle is the quotient of the side opposite by the hypotenuse. Thus, the sine of angle BAC is $\frac{BC}{AC}$, and the sine of ACD is $\frac{AD}{AC}$. Dividing one by the other, the common term AC cancels out, and the index of refraction equals $\frac{BC}{AD} = \frac{v}{v'}$, as before. The two definitions are therefore equivalent to each other. For the construction to find the refracted ray, see the Appendix.

III. *The planes of the angles of incidence and refraction coincide.*

275. Refraction through Plate Glass. — Draw a heavy black line on a sheet of paper, and place over it a thick plate of glass, covering a part of the line. Look obliquely through the glass; the line will appear broken at the edge of the plate, the part under the glass appearing laterally displaced (Fig. 249).

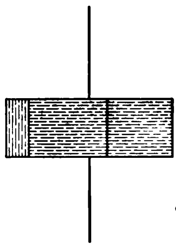


FIGURE 249. — IMAGE OF LINE DISPLACED.

To explain this, let MN (Fig. 250) represent a thick plate of glass, and AB a ray of light incident obliquely upon it. If the path of the ray be determined, the emergent ray will be parallel to the incident ray. Hence, the apparent position of an object viewed through a plate of glass is at one side of its true position.

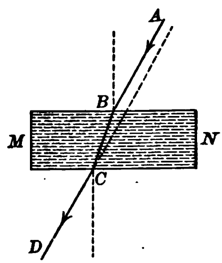


FIGURE 250. — INCIDENT AND EMERGENT RAYS PARALLEL.

276. A Prism. — Let ABC (Fig. 251) represent a section of a glass prism made by a plane perpendicular to the refracting edge A. Also, let LI be a ray incident on the face BA. This ray will be refracted along IE, and entering the air at the point E will be refracted again, taking the direction EO.

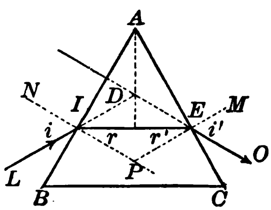


FIGURE 251.—PATH OF LIGHT THROUGH PRISM.

Reflect across the table a strong beam of light and intercept it with a sheet of green glass. Let this ribbon of green light be incident on a prism of small refracting angle in such a manner that only part of the beam passes through the prism. Two lines of light may be traced through the

dust of the room or by means of smoke. By turning the prism about its axis, the angle between these lines of light can be varied in size. It is the angle of deviation, represented by the angle *D* in the figure. The angle of deviation is least when the angles of incidence and emergence are equal; this occurs when the path of the ray through the prism is equally inclined to the two faces.

277. Atmospheric Refraction. — Light coming to the eye from any heavenly body, as a star, unless it is directly overhead, is gradually bent as it passes through the air on account of the increasing density of the atmosphere near the earth's surface. Thus, if *S* in Fig. 252 is the real position of a star, its apparent position will be *S'* to an observer at *E*.

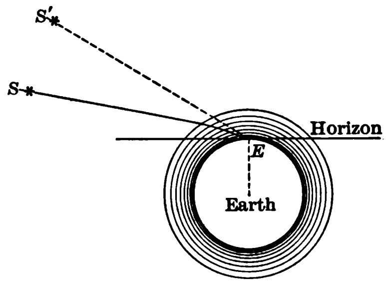


FIGURE 252. — ATMOSPHERIC REFRACTION.

Such an object appears higher above the horizon than its real altitude. The sun rises earlier on account of atmospheric refraction than it otherwise would, and for the same reason it sets later. Twilight, the mirage of the desert, and the looming of distant objects are phenomena of atmospheric refraction.


FIGURE 253. — TOTAL INTERNAL REFLECTION.

278. Total Internal Reflection. — Take the apparatus of § 271 and place the cardboard against the end of the jar so that the slit is near the bottom (Fig. 253). Reflect a strong beam of light up through the water and incident on its under surface just back of the center of the protractor scale. Adjust the slit so that the beam shall be incident at an angle a little greater than 50°. It will be reflected back into the water as from a plane mirror.

As the angle of refraction is always greater than the angle of incidence when the light passes from water into air, it is evident that there is an incident angle of such a value that the corresponding angle of refraction is 90°, that is, the refracted light is parallel to the surface. If the angle of incidence is still further increased, the light no longer passes out into the air, but suffers *total internal reflection.*

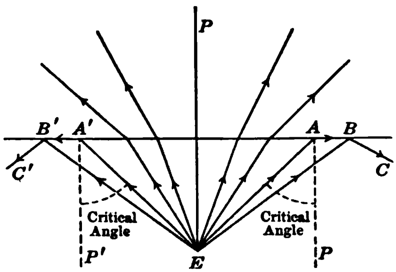


FIGURE 254. — CRITICAL ANGLE.

279. The Critical Angle. — *The critical angle* is the angle of incidence corresponding to an angle of refraction of 90°. This angle varies with the index of refraction of the substance. It is about 49° for water, 42° for crown glass, 38° for flint glass, and 24° for diamond.

Of all the rays diverging from a point at the bottom of a pond and incident on the surface, only those within a cone whose semi-angle is 49° pass into the air. All those incident at a larger angle undergo total internal reflection (Fig. 254). Hence, an observer under water sees all objects outside as if they were crowded into this cone; beyond this he sees by reflection objects on the bottom of the pond.

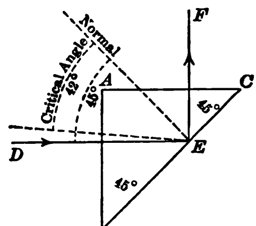


FIGURE 255. — TOTAL REFLECTION BY PRISM.

Total reflection in glass is shown by means of a prism whose cross section is a right-angled isosceles triangle (Fig. 255). A ray incident normally on either face about the right angle enters the prism without refraction,

and is incident on the hypotenuse at an angle of 45°, which is greater than the critical angle. The ray therefore suffers total internal reflection and leaves the prism at right angles to the incident ray. A similar prism is sometimes used in a projecting lantern for making the image erect (Fig. 256). It would otherwise be inverted with respect to the object.

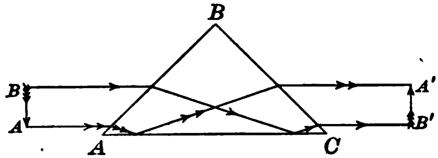


FIGURE 256. — ERECTING PRISM.

Questions and Problems

1. Why are reflectors back of wall lamps frequently made concave at the outer edge and convex in the central part?

2. Show that atmospheric refraction increases the length of daylight.

3. A plane mirror is revolved through an angle of 20°. Show by diagram that a ray of light incident on the mirror will be displaced 40°.

4. Show that the deviation of a ray of light by a glass prism is increased by increasing the angle of the prism.

5. Show that the deviation of a ray of light by a prism is increased by increasing the index of refraction.

6. Why does the full moon when seen near the horizon appear just a little elliptical, the longer axis being horizontal?

7. Why does a stream of water, to one standing on its bank, appear less than its true depth?

8. A genuine diamond is distinctly visible in carbon disulphide, a paste or false diamond is nearly invisible. Explain. (The paste diamond is flint glass.)

9. What peculiarity will the image of an object have if the mirror is convex cylindrical?

10. In spearing a fish from a boat would you strike directly at the apparent position of the fish? Explain.

11. Show by diagram the apparent displacement of a body as seen by looking obliquely at it through a plate glass window.

12. Why is powdered glass opaque?

13. Show by diagram that a triangular prism of air within water has the opposite effect on the direction of a ray of light passing through it that a prism of water in air has.

V. LENSES

280. Kinds of Lenses. — *A lens is a portion of a transparent substance* bounded by two surfaces, one or both being

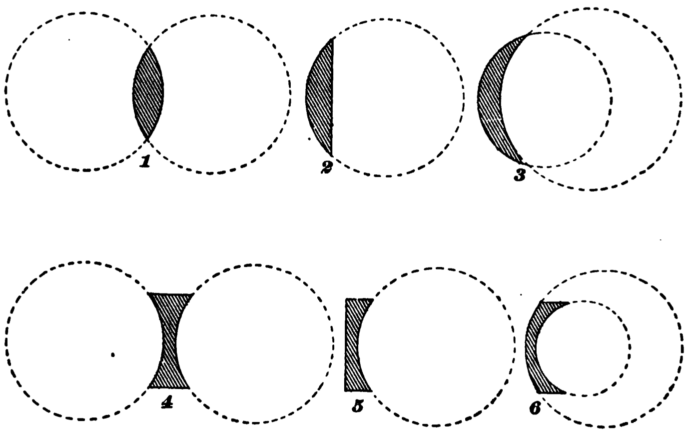


FIGURE 257. — FORMS OF LENSES.

curved. The curved surfaces are usually spherical (Fig. 257). Lenses are classified as follows:

<table>
<tr><td>1. Double-convex, — both surfaces convex . .</td><td rowspan="3">Converging lenses, thicker at the middle than at the edges.</td></tr>
<tr><td>2. Plano-convex, — one surface convex, one plane . . . .</td></tr>
<tr><td>3. Concavo-convex, — one surface convex, one concave . . . .</td></tr>
<tr><td>4. Double-concave, — both surfaces concave . .</td><td rowspan="3">Diverging lenses, thinner at the middle than at the edges.</td></tr>
<tr><td>5. Plano-concave, — one surface concave, one plane . . . .</td></tr>
<tr><td>6. Convexo-concave, — one surface concave, one convex . . . .</td></tr>
</table>

The concavo-convex and the convexo-concave lenses are frequently called *meniscus* lenses. The double-convex lens may be regarded as the type of the converging class of lenses, and the double-concave lens of the diverging class.

281. Definition of Terms relating to Lenses. — The centers of the spherical surfaces bounding a lens are the *centers of curvature.* The *optical center* is a point such that any ray passing through it and the lens suffers no change of direction. In lenses whose surfaces are of equal curvature, the optical center is their center of volume, as O, in Fig. 258. In plano-lenses, the optical center is the middle point of the curved face. The straight line, CC', through the centers of curvature, is the *principal axis*, and any other straight line through the optical center, as EH, is a *secondary axis.* The normal at any point of the surface is the radius of the sphere drawn

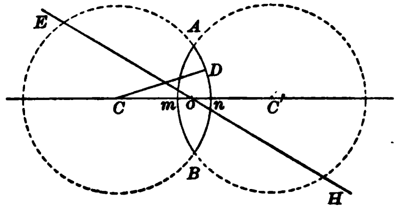


FIGURE 258. — OPTICAL CENTER OF LENS.

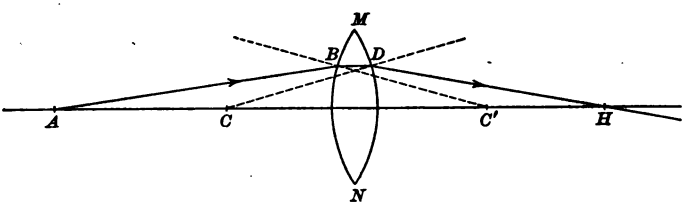


FIGURE 259. — TRACING RAY THROUGH CONVERGING LENS.

to that point; thus CD is the normal to the surface AnB at D.

282. Tracing Rays through Lenses. — A study of Figs. 259 and 260 shows that the action of lenses on rays of

light traversing them is similar to that of prisms, and conforms to the principle illustrated in § 276. A ray is always refracted *toward* the perpendicular on entering a denser medium (glass) and *away from* it on entering a medium of less optical density. Thus we see that the *convex lens bends a ray toward the principal axis*, while the *concave lens* (Fig. 260) *bends it away from this axis*.

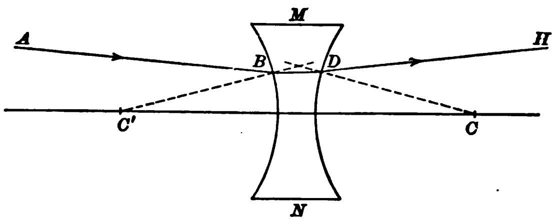


FIGURE 260. — TRACING RAY THROUGH DIVERGING LENS.

(For tracing the path of a ray geometrically, consult Appendix V.)

283. The Principal Focus. — Hold a converging lens so that the rays of the sun fall on it parallel to its principal axis. Beyond the lens hold a sheet of white paper, moving it until the round spot of light is smallest and brightest. If held steadily, a hole may be burned through the paper. This spot marks the *principal focus* of the lens, and its distance from the optical center is the *principal focal length.*

For double-convex lenses, the two faces having the same radius of curvature, *the principal focus is at the center of curvature when the index of refraction is 1.5.* If the index is greater than 1.5, the focal length is less than the radius of curvature; if less than 1.5, it is greater than this radius.

Converging lenses are sometimes called *burning glasses* because of their power to focus the heat rays, as shown in the experiment.

Figure 261 shows that parallel rays are made to converge toward the principal focus F by a converging lens, and the focus is *real;* on the other hand, Fig. 262 illustrates the diverging effect of a concave lens on parallel rays; the focus F is now *virtual* because the rays after passing through the lens only apparently come from F. In general, converging lenses increase the convergence of light, while diverging lenses decrease it.

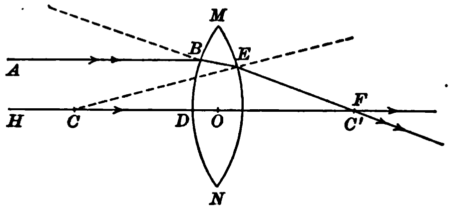


FIGURE 261. — PRINCIPAL FOCUS OF A CONVERGING LENS.

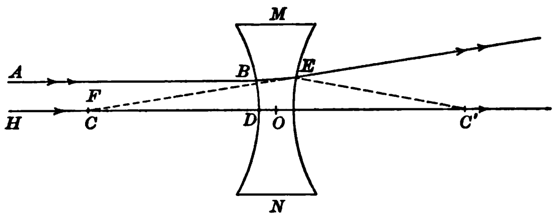


FIGURE 262. — PRINCIPAL FOCUS OF A DIVERGING LENS.

284. Conjugate Foci of Lenses. — If a pencil of light diverges from a point and is incident on the lens, it is focused at a point on the axis through the radiant point.

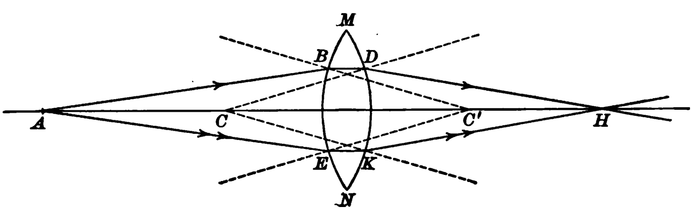


FIGURE 263. — CONJUGATE FOCI, CONVERGING LENS.

These points are called *conjugate foci*, for the same reason as in mirrors.

In Fig. 263 a pencil of rays BAE diverges from A and is focused by the lens at the point H. It is evident that if the rays diverge from H, they would be brought to a focus at A. Hence A and H are *conjugate foci*.

285. Images by Lenses. — Place in a line on the table in a darkened room a lamp, a converging lens of known focal length, and a white screen. If, for example, the focal length of the lens is 30 cm., place the lamp about 70 cm. from it, or more than twice the focal length, and move the screen until a clearly defined image of the lamp appears on it. This image will be inverted, smaller than the object, and situated between 30 cm. and 60 cm. from the lens. By placing the lamp successively at 60 cm., 50 cm., 30 cm., and 20 cm., the images will differ in position and size, and in the last case will not be received on the screen, but may be seen by looking through the lens toward the lamp. If a diverging lens be used, no image can be received on the screen because they are all virtual.

The results of such an experiment may be summarized as follows :

I. When the object is at a finite distance from a converging lens, and farther than twice the focal length, the

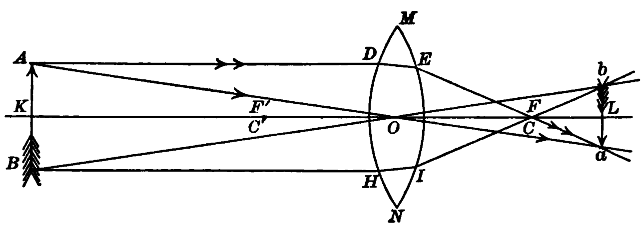


FIGURE 264. — OBJECT FARTHER THAN TWICE FOCAL LENGTH FROM LENS.

image is real, inverted, at a distance from the lens of more than once and less than twice the focal length, and smaller than the object (Fig. 264).

II. When the object is at a distance of twice the focal length from a converging lens, the image is real, inverted,

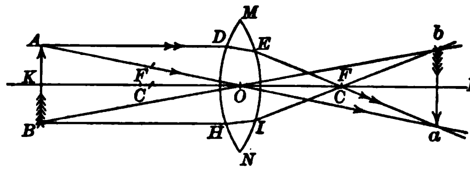


FIGURE 265. — OBJECT TWICE FOCAL LENGTH FROM LENS.

at the same distance from the lens as the object, and of the same size (Fig. 265).

III. When the object is at a distance from a converging lens of less than twice and more than once its

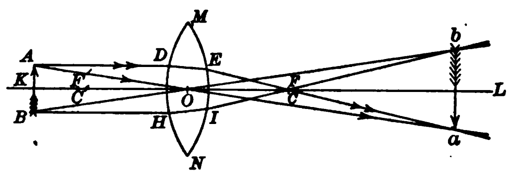


FIGURE 266. — OBJECT LESS THAN TWICE FOCAL LENGTH FROM LENS.

focal length, the image is real, inverted, at a distance of more than twice the focal length, and larger than the object (Fig. 266).

IV. When the object is at the principal focus of a converging lens, no distinct image is formed (Fig. 267).

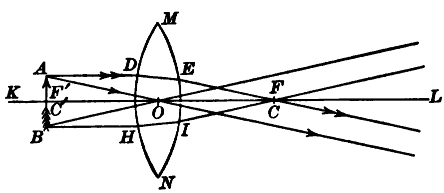


FIGURE 267. — OBJECT AT PRINCIPAL FOCUS.

V. When the object is between a converging lens and its principal focus, the image is virtual, erect, and enlarged (Fig. 268).

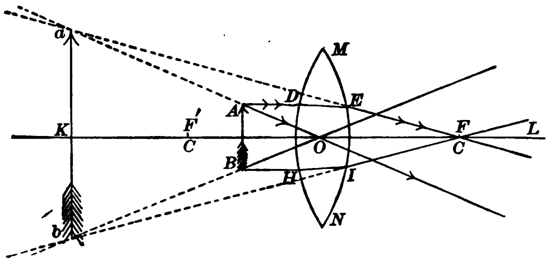


FIGURE 268. — OBJECT LESS THAN FOCAL LENGTH FROM LENS.

VI. With a diverging lens, the image is always virtual, erect, and smaller than the object (Fig. 269).

286. Graphic Construction of Images by Lenses. — The image of an object by a lens consists of the images of its points. If the object is represented by an arrow, it is

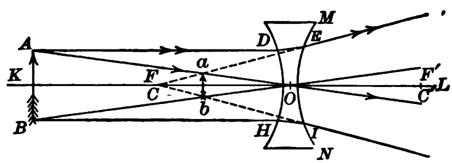


FIGURE 269. — IMAGE VIRTUAL IN DIVERGING LENS.

necessary to find only the images of its extremities. This is readily done by following two general directions:

First. Draw secondary axes through the ends of the arrow. These represent rays that suffer no change in direction because they pass through the optical center (§ 281).

Second. Through the ends of the arrow draw rays parallel to the principal axis. After leaving the lens, these pass through the principal focus (§ 283).

The intersection of the two refracted rays from each extremity will be its image.

To illustrate. Let *AB* be the object and *MN* the lens (Figs. 264–269). Rays along secondary axes through *O* pass through the lens without any change in direction. The rays *AD* and *BH*, parallel to the principal axis, are refracted in the lens along *DE* and *HI* respectively, and emerge from the lens in a direction which passes through the principal focus *F*. The intersection of *Aa* with *Ea* is the image of *A*, and that of *Bb* with *Ib* is the image of *B*. Other rays from *A* and *B* also pass through *a* and *b* respectively, and therefore *ab* is the image of *AB*. The image is virtual when the intersection of the refracted rays is on the same side of the lens as the object. The relative size of object and image is the same as their relative distance from the lens.

287. Spherical Aberration in Lenses. — If rays from any point be drawn to different parts of a lens, and their

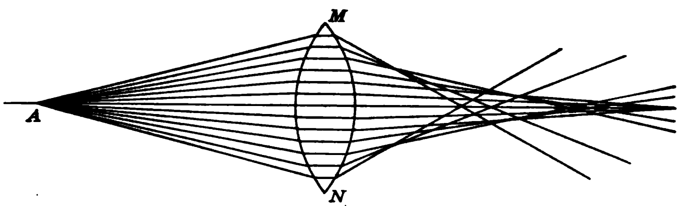


FIGURE 270. — SPHERICAL ABERRATION.

directions be determined after refraction, it will be found that those incident near the edge of the lens cross the principal axis, after emerging, nearer the lens than those incident near the middle (Fig. 270). The principal focal length for the marginal rays is therefore less than for central rays. This indefiniteness of focus is called *spherical aberration by refraction*, the effect of which is to lessen the

distinctness of images formed by the lens. In practice a round screen, called a *diaphragm*, is used to cut off the marginal rays; this renders the image sharper in outline, but less bright. In the large lenses used in telescopes the curvature of the lens is made less toward the edge, so that all parallel rays are brought to the same focus.

288. Formula for Lenses. — The triangles AOK and aOL in Fig. 271 are similar. Hence, $\frac{AK}{aL} = \frac{KO}{LO}$. If the lens is *thin*, a straight line connecting D and H will pass very nearly through the optical

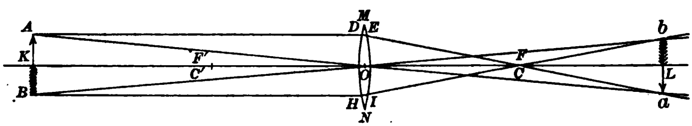


FIGURE 271. — RELATION BETWEEN OBJECT AND IMAGE.

center O. Then DFO is a triangle similar to aFL, and $\frac{DO}{aL} = \frac{OF}{LF}$. Since DO is equal to AK, the first members of the two equations above are equal to each other, and therefore $\frac{KO}{LO} = \frac{OF}{LF}$. Put $KO = p$, $LO = q$, and $OF = f$. Then $LF = q - f$, and

$$\frac{p}{q} = \frac{f}{q-f}.$$

Clearing of fractions and dividing through by pqf, we have

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}. \quad . \quad . \quad . \quad . \quad . \quad \text{(Equation 32)}$$

By measuring p and q we may compute f. For diverging lenses f and q are negative.

Questions and Problems

1. How can a convex lens be distinguished from a concave one?

2. Why does common window glass often give distorted images of objects viewed through it?

3. How can the principal focal length of a concave spherical mirror be found?

4. Given a collection of spectacle lenses; select the concave from the convex.

5. Why do so many cheap mirrors give distorted images?

6. If an oarsman sticks his oar into the water obliquely, why does it appear broken at the point of entrance?

7. Concave spherical mirrors are often mounted in frames to be used as hand glasses. Such mirrors are usually made by silvering one face of a lens. Why can several images be seen in such a mirror?

8. When is the distance between the object and its real image as formed by a converging lens the least possible?

9. The focal length of a camera lens is two inches. How far must the sensitized plate be from the lens, when the object is distant 100 ft.?

10. If a reading glass has a focal length of 16 in. and in its use is held 10 in. from the book, what is the position of the virtual image?

11. An object 100 cm. in front of a converging lens gives an image 25 cm. back of the lens. What is the focal length of the lens?

12. Show by diagram what effect it has on the image of an object by a diverging lens to move it farther away from the lens.

13. Why is a convex mirror used on an automobile to view objects back of the driver, instead of a plane mirror?

14. In a diverging lens, show that a pencil of light that converges to a point beyond the focus of the lens issues as a diverging pencil.

15. Where must a diverging lens be placed to render parallel a converging pencil of light?

VI. OPTICAL INSTRUMENTS

289. The Magnifying Glass, or *simple microscope*, is a double-convex lens, usually of short focal length. The object must be placed nearer the lens than its principal focus. The image is then virtual, erect, and enlarged. If *AB* is the object in Fig. 272, the virtual image is *ab*; and if the eye be placed near the lens on the side opposite

the object the virtual image will be seen in the position of the intersection of the rays produced, as at *ab*.

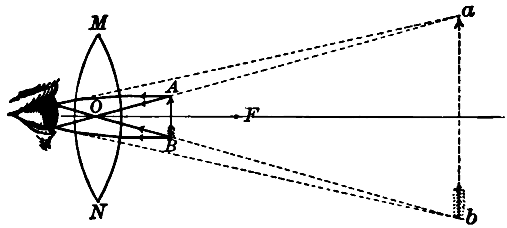


FIGURE 272. — MAGNIFYING GLASS.

290. The Compound Microscope (Fig. 273) is an instrument designed to obtain a greatly enlarged image of very small objects. In its simplest form it consists of a converging lens *MN* (Fig. 274), called the *object glass* or *objective*, and another converging lens *RS*, called the *eye-piece*. The two lenses are mounted in the ends of the tube of Fig. 273. The object is placed on the stage just under the objective, and a little beyond its principal focus. A real image *ab* (Fig. 274) is formed slightly nearer the eye-piece than its focal length. This image formed by the objective is viewed by the eyepiece, and the latter gives an enlarged virtual image. (Why?) Both the objective and the eyepiece produce magnification.

FIGURE 273. — MICROSCOPE.

291. The Astronomical Telescope. — The system of lenses in the refracting astronomical telescope (Fig. 275) is similar to that of the compound microscope. Since it is intended to view distant objects, the objective *MN* is of

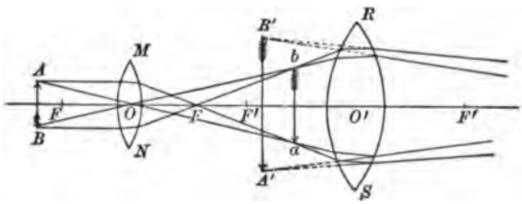


FIGURE 274. — TRACING RAYS TO FORM IMAGE

large aperture and long focal length. The real image given by it is the object for the eyepiece, which again forms a virtual image for the eye of the observer. The magnification is the ratio of the focal lengths of the objective and the eyepiece. The objective must be large, for the purpose of collecting enough light to permit large

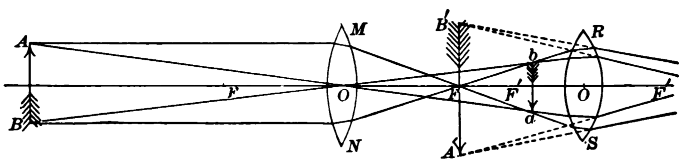


FIGURE 275. — IMAGE IN ASTRONOMICAL TELESCOPE.

magnification of the image without too great loss in brightness.

Figure 275 shows that the image in the astronomical telescope is inverted. In a terrestrial telescope the image is made erect by introducing near the eyepiece two double-convex lenses, in such relation to each other and to the first image that a second real image is formed like the first, but erect.

292. Galileo's Telescope. — The earliest form of telescope was invented by Galileo. It produces an erect image by the use of a diverging lens for the eyepiece (Fig. 276). This lens is placed between the objective and the real image, *ab*, which would be formed by the objective if the eyepiece were not interposed. Its focus is practically at the image *ab*, and the rays of light issue from it slightly

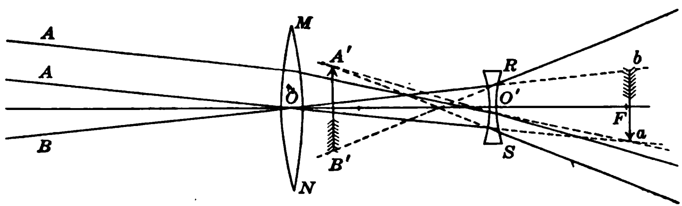


FIGURE 276. — GALILEO'S TELESCOPE.

divergent for distant objects. The image is therefore at $A'B'$ instead of at *ab*, and it is erect and enlarged. This telescope is much shorter than the astronomical telescope, for the distance between the lenses is the difference of their focal lengths instead of their sum. In the *opera glass* two of Galileo's telescopes are attached together with their axes parallel.

293. The Projection Lantern is an apparatus by which a greatly enlarged image of an object can be projected on a screen. The three essentials of a projection lantern are a strong light, a condenser, and an objective. The light may be the electric arc light, as shown in Fig. 277, the calcium light, or a large oil burner. The condenser *E* is composed of a pair of converging lenses; its chief purpose is the collection of the light on the object by refraction, so as to bring as much as possible on the screen. The object *AB*, commonly a drawing or a photograph

Moving Picture Film.

Most moving picture cameras take from 16 to 120 pictures per second.

on glass, is placed near the condenser SS, where it is strongly illuminated. The objective, MN, is a combination of lenses, acting as a single lens to project on the screen a real, inverted, and enlarged image of the object.

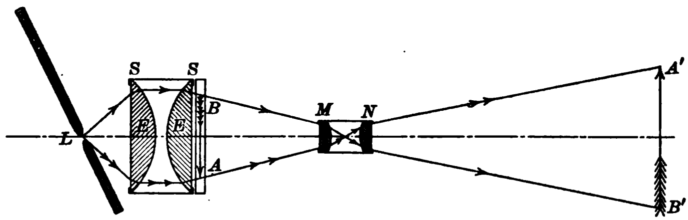


FIGURE 277. — PROJECTION LANTERN.

294. The Photographer's Camera consists of a box BC (Fig. 278), adjustable in length, blackened inside, and provided at one end with a lens or a combination of lenses, acting as a single one, and at the other with a holder for the sensitized plate. If by means of a rack and pinion the lens L' be properly focused for an object in front of it, an inverted image will be formed on the sensitized plate E. The light acts on the salts contained in the sensitized film, producing in them a modification which, by the processes of "developing" and "fixing," becomes a permanent negative picture of the object. When a "print" is made from this negative, the result is a positive picture.

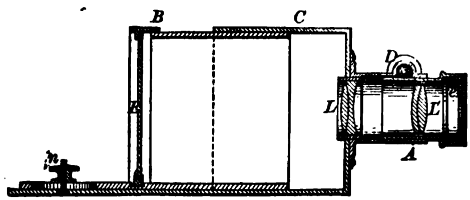


FIGURE 278. — CAMERA.

295. The Eye. — The eye is like a small photographic camera, with a converging lens, a dark chamber, and a

sensitive screen. Figure 279 is a vertical section through the axis. The outer covering, or *sclerotic* coat *H*, is a thick opaque substance, except in front, where it is extended as a transparent coat, called the *cornea A*. Behind the cornea is a diaphragm *D*, constituting the colored part of the eye, or the *iris*. The circular opening in the iris is the *pupil*, the size of which changes with the intensity of light. Supported from the walls of the eye,

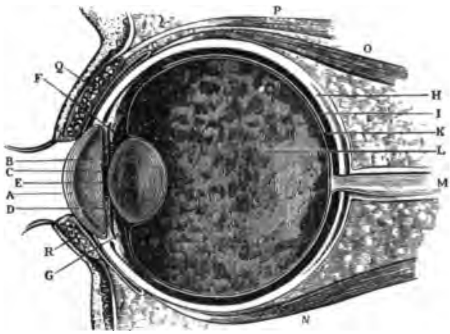


FIGURE 279. — SECTION OF EYE.

just back of the iris, is the *crystalline lens E*, a transparent body dividing the eye into two chambers; the anterior chamber between the cornea and the crystalline lens is a transparent fluid called the *aqueous humor*, while the large chamber behind the lens is filled with a jellylike substance called the *vitreous humor*. The *choroid coat* lines the walls of this posterior chamber, and on it is spread the *retina*, a membrane traversed by a network of nerves, branching from the *optic nerve M*. The choroid coat is filled with a black pigment, which serves to darken the cavity of the eye, and to absorb the light reflected internally.

296. Sight. — When rays of light diverge from the object and enter the pupil of the eye they form an inverted image on the retina (Fig. 280) precisely as in the photographic camera. In place of the sensitized plate is the sensitive retina, from which the stimulus is carried to the brain along the optic nerve.

In the camera the distance between the lens and the screen or plate must be adjusted for objects at different distances. In the eye the corresponding distance is fixed, and the adjustment for distinct vision is made by unconsciously changing the curvature of the front surface of

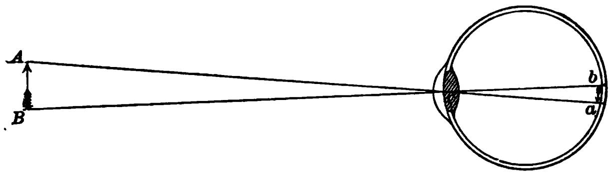


FIGURE 280. — IMAGE ON RETINA.

the crystalline lens by means of the ciliary muscle F, G (Fig. 279). This capability of the lens of the eye to change its focal length for objects at different distances is called *accommodation.*

297. The Blind Spot. — There is a small depression where the optic nerve enters the eye. The rest of the retina is covered with microscopic rods and cones, but there are none in this depression, and it is insensible to light. It is

FIGURE 281. — TO FIND BLIND SPOT.

accordingly called the *blind spot.* Its existence can be readily proved by the help of Fig. 281. Hold the book with the circle opposite the right eye. Now close the left eye and turn the right to look at the cross. Move the book toward the eye from a distance of about a foot, and a position will readily be found where the black circle will disappear. Its image then falls on the blind spot. It may be brought into view again by moving the book either nearer the eye or farther away.

298. The Prism Binocular. — While the opera glass (§ 292) is compact and gives an erect image, it has only a small field of view, and is usually made to magnify only three or four times. For the purpose of obtaining a larger field of view with equal compactness, the *prism binocular* has been devised. The desired length has been obtained by the use of two total reflecting prisms (Fig. 282), by means of which the light is reflected forward and back again in the tube. Not only is compactness secured in this manner, but the reflections in the prisms increase the focal length of the objective and serve to give an erect image without "perversion."

FIGURE 282. — PRISM BINOCULAR.

299. Defects of the Eye. — A normal eye in its passive or relaxed condition focuses parallel rays on the retina. The defects of most frequent occurrence are near-sightedness, far-sightedness, and astigmatism.

If the relaxed eye focuses parallel rays in front of the retina (Fig. 283), it is *near-sighted.* The length of the eyeball from front to back is then too great for the focal length of the crystalline lens. The correction consists in placing in front of the eye a diverging lens that makes with the lens of the eye a less convergent system than the crystalline lens itself. If the focal length of the diverging lens is equal to the greatest distance of distinct vision for the near-sighted eye, and if

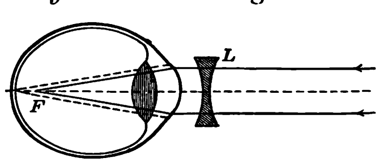


FIGURE 283. — NEAR-SIGHTEDNESS.

this lens is held close to the eye, parallel rays from a distant object will enter the eye as if they came from the principal focus of the lens, the image falls on the retina, and vision is made distinct.

If the relaxed eye focuses parallel rays from distant objects behind the retina, it is *far-sighted.* The length of the eyeball is then too short to correspond with the focal length of the crystalline lens. The correction consists in placing in front of the eye a converging lens (Fig. 284), making with the lens of the eye a more converging system than the eye lens alone. Light from a near object then enters the eye as if it came from a distant one and vision becomes distinct.

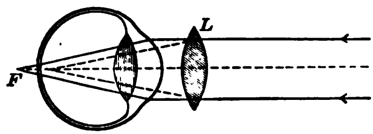


FIGURE 284. — FAR-SIGHTEDNESS.

Sometimes the front of the cornea has different curvatures in different planes through the axis; that is, it has a somewhat cylindrical form. Persons with such an eye do not see with equal distinctness all the figures on the face of a watch. This defect is known as *astigmatism.* It is corrected by the use of a lens, one surface of which at least is not spherical but differs from it in the opposite sense to that of the defective eye. The astigmatism of the two eyes is not usually the same.

VII. DISPERSION

300. Analysis of White Light. The Solar Spectrum. — Darken the room, and by means of a mirror hinged outside the window, reflect a pencil of sunlight into the room. Close the opening in the window with a piece of tin, in which is cut a very narrow vertical slit. Let the ribbon of sunlight issuing from the slit be incident obliquely on a glass prism (Fig. 285). A many-colored band, gradually changing from red at one end through orange, yellow, green, blue, to violet

at the other, appears on the screen. If a converging lens of about 30 cm. focal length be used to focus an image of the slit on the screen, and the prism be placed near the principal focus, the colored images of the slit will be more distinct.

FIGURE 285. — ANALYSIS OF WHITE LIGHT.

This experiment shows that white or colorless light is a mixture of an infinite number of differently colored rays, of which the red is refracted least and the violet most. The brilliant band of light consists of an indefinite number of colored images of the slit; it is called the ***solar spectrum***, and the opening out or separating of the beam of white light is known as ***dispersion***.

301. Synthesis of Light. — Project a spectrum of sunlight on the screen. Now place a second prism like the first behind it, but reversed in position (Fig. 286). There will be formed a colorless image, slightly displaced on the screen.

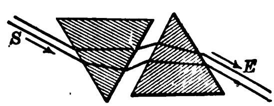


FIGURE 286. — REFORMING WHITE LIGHT.

The second prism reunites the colored rays, making the effect that of a thick plate of glass (§ 275). The recomposition of the colored rays into white light may also be effected by receiving them on a concave mirror or a large convex lens.

302. Chromatic Aberration. — Let a beam of sunlight into the darkened room through a round hole in a piece of cardboard. Pro-

ject an image of this aperture on the screen, using a double-convex lens for the purpose. The round image will be bordered with the spectral colors.

This experiment shows that the lens refracts the rays of different colors to different foci. This defect in lenses is known as *chromatic aberration.* The violet rays, being more refrangible than the red, will have their focus nearer to the lens than the red, as shown in Fig. 287, where *v* is the principal focus for violet light and *r* for red. If a screen were placed at *x*, the image would be bordered with red, and if at *y* with violet.

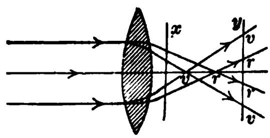


FIGURE 287. — CHROMATIC ABERRATION.

303. The Achromatic Lens. — With a prism of crown glass project a spectrum of sunlight on the screen, and note the length of the spectrum when the prism is turned to give the least deviation (§ 276). Repeat the experiment with a prism of flint glass having the same refracting angle. The spectrum formed by the flint glass will be about twice as long as that given by crown glass, while the position of the middle of the spectrum on the screen is about the same in the two cases. Now use a flint glass prism whose refracting angle is half that of the crown glass one. The spectrum is nearly equal in length to that given by the crown glass prism, but the deviation of the middle of it is considerably less. Finally, place this flint glass prism in a reversed position against the crown glass one (Fig. 288). The image of the aperture is no longer colored, and the deviation is about half that produced by the crown glass alone.

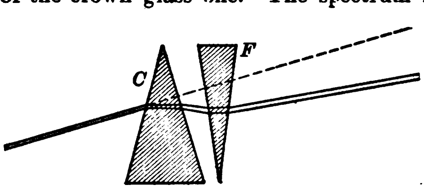


FIGURE 288. — ACHROMATIC PRISM.

In 1757 Dollond, an English optician, combined a double-convex lens of crown glass with a plano-concave lens of

flint glass so that the dispersion by the one neutralized that due to the other, while the refraction was reduced about half (Fig. 289). Such a lens or system of lenses is called *achromatic*, since images formed by it are not fringed with the spectral colors.

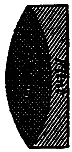


FIGURE 289. — ACHROMATIC LENS.

304. The Rainbow.—Cement a crystallizing beaker 12 or 15 cm. in diameter to a slate slab. Fill the beaker with water through a hole drilled in the slate. Support the slate in a vertical plane and direct a ribbon of white light upon the beaker at a point about 60° above its horizontal axis, as *SA* (Fig. 290). The light may be traced through the water, part of it issuing at the back at *B* as a diverging pencil, and a part reflected to *C* and issuing as spectrum colors along *CD*. If other points of incidence be tried, the colors given by the reflected portion are very indistinct except at 70° below the axis. After refraction at this point, the light can be traced through the water, issuing as spectral colors after having suffered two refractions and two reflections.

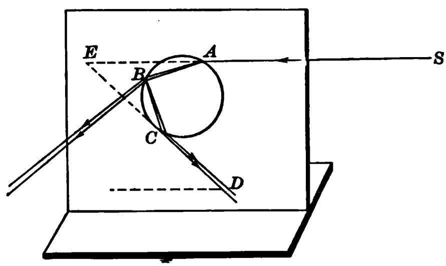


FIGURE 290. — ILLUSTRATING RAINBOW.

The experiment shows that the light must be incident at definite angles to give color effects. The red constituent of white light incident at about 60° keeps together after reflection and subsequent refraction; that is, the red rays are practically parallel and thus have sufficient intensity to produce a red image. The same is true of the violet light incident at about 59° from the axis. The other spectral colors arrange themselves in order between the red and violet.

For light incident at about 70° from the axis a similar

spectrum band is formed by light which has suffered two refractions and two reflections.

So when sunlight falls on raindrops the light is dispersed and a rainbow is formed. Two bows are often visible, the *primary* and the *secondary*. The primary is the inner and brighter one, formed by a single internal reflection. It is distinguished by having the red on the outside and the violet on the inside. The secondary bow, formed by two internal reflections, is fainter, and has the order of colors reversed. Figure 291 shows the relative positions of the sun, the observer, and the raindrops which form the bows. It should be noted that all drops in the line *vE* send violet light to the eye, those along *rE* send red light, and those between the two send the intermediate colors.

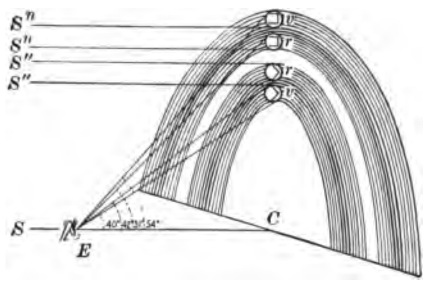


FIGURE 291. — PRIMARY AND SECONDARY BOWS.

305. Continuous Spectra. — Throw on a screen the spectrum of the electric arc, using preferably for the purpose a hollow prism filled with carbon bisulphide. The spectrum will be composed of colors from red at one end through orange, yellow, green, blue, and violet at the other without interruptions or gaps.

The experiment illustrates *continuous spectra*, that is, spectra without breaks or gaps in the color band. *Solids, liquids, and dense vapors and gases, when heated to incandescence, give continuous spectra.*

306. Discontinuous Spectra. — Project on the screen the spectrum of the electric light. Place in the arc a few crystals of sodium nitrate.

The intense heat will vaporize the sodium, and a spectrum will be obtained consisting of bright colored lines, one red, one yellow, three green, and one violet, the yellow being most prominent.

The experiment illustrates *discontinuous* or *bright line spectra*, that is, spectra consisting of one or more bright lines of color separated by dark spaces. *Rarefied gases and vapors, when heated to incandescence, give discontinuous spectra.*

307. Absorption Spectra. — Project on the screen the spectrum of the electric light. Between the lamp and the slit *S* (Fig. 292) vaporize metallic sodium in an iron spoon so placed that the white light passes through the heated sodium vapor before dispersion by the prism. A dark line will appear on the screen in the yellow of the spectrum at the place where the bright line was obtained in the preceding experiment.

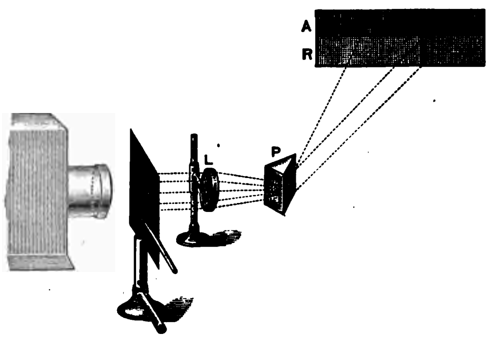


FIGURE 292. — ABSORPTION SPECTRUM.

The experiment illustrates an *absorption*, *reversed* or *dark line spectrum*. The dark line is produced by the absorption of the yellow light by sodium vapor. *Gases and vapors absorb light of the same refrangibility as they emit at a higher temperature.*

308. The Fraunhofer Lines. — Show on the screen a carefully focused spectrum of sunlight. Several of the colors will appear crossed with fine dark lines (Fig. 293).

Fraunhofer was the first to notice that some of these lines coincide in position with the bright lines of certain

artificial lights. He mapped no less than 576 of them, and designated the more important ones by the letters *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*, the first in the extreme red and the last in the violet. For this reason they are referred to as the Fraunhofer lines. In recent years the number of these lines has been found to be practically unlimited.

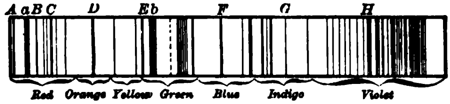


FIGURE 293. — FRAUNHOFER LINES.

In the last experiment it was shown that sodium vapor absorbs that part of the light of the electric arc which is of the same refrangibility as the light emitted by the vapor itself. Similar experiments with other substances show that every substance has its own absorption spectrum. These facts suggested the following explanation of the Fraunhofer lines: The heated nucleus of the sun gives off light of all degrees of refrangibility. Its spectrum would therefore be continuous, were it not surrounded by an atmosphere of metallic vapors and of gases, which absorb or weaken those rays of which the spectra of these vapors consist. Hence, the parts of the spectrum which would have been illuminated by those particular rays have their brightness diminished, since the rays from the nucleus are absorbed, and the illumination is due to the less intense light coming from the vapors. These absorption lines are not lines of no light, but are lines of diminished brightness, appearing dark by contrast with the other parts of the spectrum.

309. The Spectroscope. — The commonest instrument for viewing spectra is the spectroscope (Fig. 294). In one of its simplest forms it consists of a prism *A*, a telescope *B*, and a tube called the *collimator* *C*, carrying an adjust-

able slit at the outer end D, and a converging lens at the other E, to render parallel the diverging rays coming from

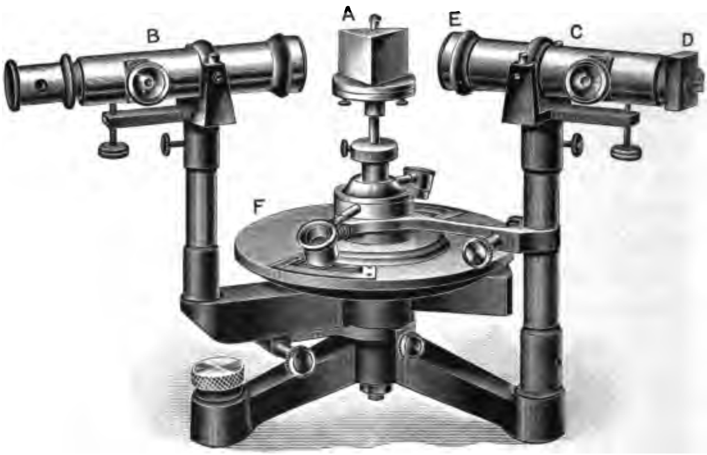


FIGURE 294. — SPECTROSCOPE.

the slit. The slit must therefore be placed at the principal focus of the converging lens. To mark the deviation of the spectral lines, there is provided on the supporting

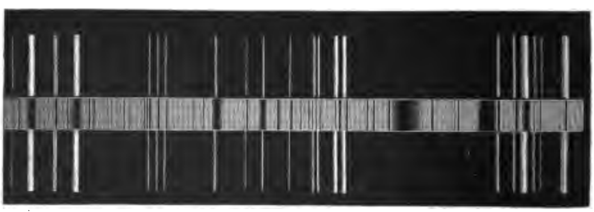
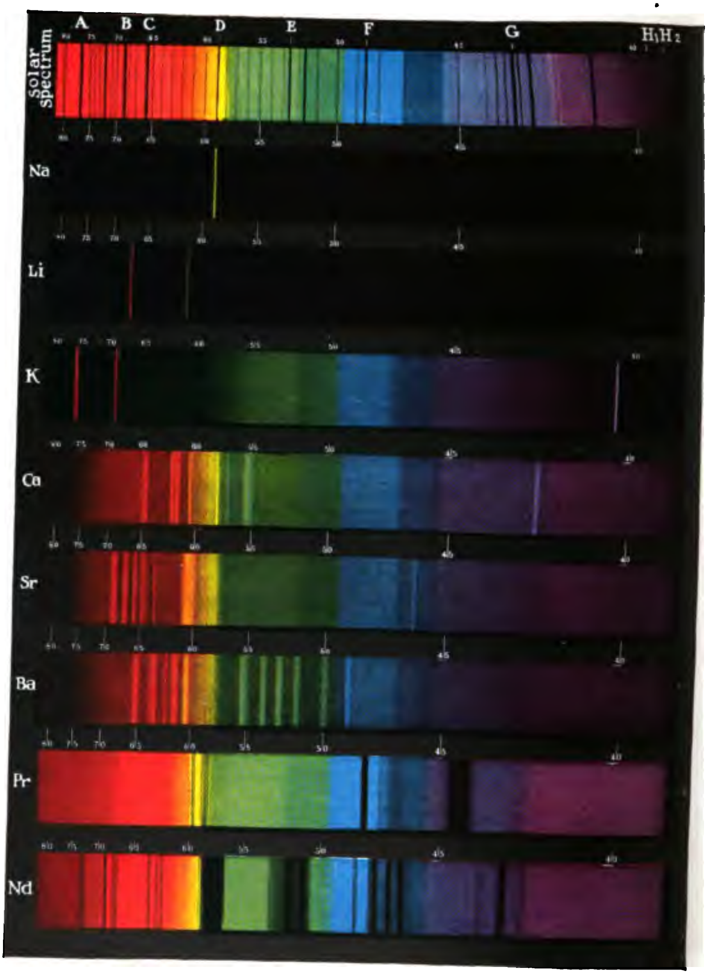


FIGURE 295. — IRON VAPOR IN THE SUN.

table a divided circle F, which is read by the aid of verniers and reading microscopes attached to the telescope arm.

The applications of the spectroscope are many and various. By an examination of their absorption spectra, normal and diseased blood



VARIOUS SPECTRA

are easily distinguished, the adulteration of substances is detected, and the chemistry of the stars is approximately determined. Figure 295 shows the agreement of a number of the spectral lines of iron with Fraunhofer lines in the solar spectrum; they indicate the presence of iron vapor in the atmosphere of the sun.

VIII. COLOR

310. The Wave Length of light determines its color. Extreme red is produced by the longest waves, and extreme violet by the shortest. The following are the wave lengths for the principal Fraunhofer lines in air at 20° C. and 760 mm. pressure :

A	Dark Red .	0.0007621 mm.	E_1	Light Green	0.0005270 mm.
B	Red . . .	6884 mm.	E_2	. . . . .	5269 mm.
C	Orange . .	6563 mm.	F	Blue . . .	4861 mm.
D_1	Yellow . .	5896 mm.	G	Indigo . .	4293 mm.
D_2	. . . . .	5890 mm.	H_1	Violet . .	3968 mm.

In white light the number of colors is infinite, and they pass into one another by imperceptible gradations of shade and wave length. Color stands related to light in the same way that pitch does to sound. In most artificial lights certain colors are either feeble or wanting. Hence, artificial lights are not generally white, but each one is characterized by the color that predominates in its spectrum.

311. Color of Opaque Bodies. — Project the solar spectrum on a white screen. Hold pieces of colored paper or cloth successively in different parts of the spectrum. A strip of red flannel appears brilliantly red in the red part of the spectrum, and black elsewhere; a blue ribbon is blue only in the blue part of the spectrum, and a piece of black paper is black in every part of the spectrum.

The experiment shows that the color of a body is due both to the light that it receives and the light that it reflects ;

that a body is red because it reflects chiefly, if not wholly, the red rays of the light incident upon it, the others being absorbed wholly or partly at its surface. It cannot be red if there is no red light incident upon it. In the same way a body is white if it reflects all the rays in about equal proportions, provided white light is incident upon it. So it appears that bodies have no color of their own, since they exhibit no color not already present in the light which illuminates them.

This truth is illustrated by the difficulty experienced in matching colors by artificial lights, and by the changes in shades some fabrics undergo when taken from sunlight into gaslight. Most artificial lights are deficient in blue and violet rays; and hence all complex colors, into which blue or violet enters, as purple and pink, change their shade when viewed by artificial light.

312. Color of Transparent Bodies. — Throw the spectrum of the sun or of the arc light on the screen. Hold across the slit a flat bottle or cell filled with a solution of ammoniated oxide of copper.[1] The spectrum below the green will be cut off. Substitute a solution of picric acid, and the spectrum above the green will be cut off. Place both solutions across the slit and the green alone remains. It is the only color transmitted by both solutions. In like manner, blue glass cuts off the less refrangible part of the spectrum, ruby glass cuts off the more refrangible, and the two together cut off the whole.

This experiment shows that the color of a transparent body is determined by the colors that it absorbs. It is colorless like glass if it absorbs all colors in like proportion, or absorbs none; but if it absorbs some colors more than others, its color is due to the mixed impression produced by the various colors passing through it.

[1] It is prepared by adding ammonia to a solution of copper sulphate, until the precipitate at first formed is dissolved.

313. Mixing Colored Lights. — Out of colored papers cut several disks, about 15 cm. in diameter, with a hole at the center for mounting them on the spindle of a whirling machine (Fig. 296), or for slipping them over the handle of a heavy spinning top. Slit them along a radius from the circumference to the center, so that two or more of them can be placed together, exposing any proportional part of each one as desired (Fig. 297). Select seven disks, whose colors most nearly represent those of the solar spectrum; put them together so that equal portions of the colors are exposed. Clamp on the spindle of the whirling machine and rotate them rapidly. When viewed in a strong light the color is an impure white or gray.

FIGURE 296. — MIXING COLORED LIGHTS.

This method of mixing colors is based on the physiological fact that a sensation lasts longer than the stimulus producing it. Before the sensation caused by one stimulus has ceased, the disk has moved, so that a different impression is produced. The effect is equivalent to superposing the several colors on one another at the same time.

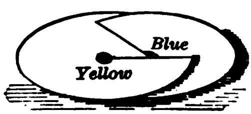


FIGURE 297. — COLORED DISKS.

314. Three Primary Colors. — If red, green, and blue, or violet disks are used, as in § 313, exposing equal portions, gray or impure white is obtained when they are rapidly rotated. If any two colors standing opposite each other in Fig. 298 are used, the result is white; and if any two alternate ones are used, the result is the intermediate one. By using the red, the green, and the violet disks, and exposing in different proportions, it has been found possible to produce any color

of the spectrum. This fact suggested to Dr. Young the theory that there are only three primary color sensations, and that our recognition of different colors is due to the excitation of these three in varying degrees.

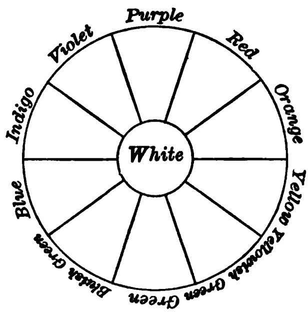


FIGURE 298. — COLOR DISK.

The color top is a standard toy provided with colored paper disks, like those of Fig. 296. When red, green, and blue disks are combined so as to show sectors of equal size, the top, when spinning in a strong light, appears to be gray. Gray is a white of low intensity. The colors of the disks are those of pigments, and they are not pure red, green, and blue.

315. Three- and Four-color Printing. — The frontispiece of this book illustrates a four-color print of much interest. Such a print is made up of very fine lines and dots of the four pigments, red, yellow, blue, and black. The various colors in the picture are mixtures of these four with the white of the paper.

The picture is made by printing the four colors one on top of the other from four copper plates, each of which represents only that part of the picture where a certain color must be used to give the proper final effect. These plates are made from four negatives. The process of preparing these negatives is as follows :

Each negative is made by taking a picture of the original colored drawing through a colored "filter," which cuts out all the colors except the one desired. A blue filter is used to prepare the plate that prints with yellow ink, a green filter to prepare the red printing plate, a red filter

for the blue printing plate, and a chrome yellow filter for the black printing plate.

A cross-lined glass screen, dividing the image into small dots, is placed in front of the negatives in the camera. Glue enamel prints are then made on copper, and the plates are etched, leaving the desired printing surface in relief.

In the frontispiece the yellow is printed first, the red over the yellow second, the blue third over the yellow and red, and the black last over the yellow, red, and blue.

When no black is used the process is known as the *three-color process.*

316. Complementary Colors. — *Any two colors whose mixture produces on the eye the impression of white light are called complementary.* Thus, red and bluish green are complementary; also orange and light blue. When complementary colors are viewed next to each other, the effect is a mutual heightening of color impressions.

Complementary colors may be seen by what is known as retinal fatigue. Cut some design out of paper, and paste it on red glass. Project it on a screen in a dark room. Look steadily at the screen for several seconds, and then turn up the lights. The design will appear on a pale green ground.

This experiment shows that the portion of the retina on which the red light falls becomes tired of red, and refuses to convey as vivid a sensation of red as of the other colors, when less intense white light is thrown on it. But it retains its sensitiveness in full for the rest of white light, and therefore conveys to the brain the impression of white light with the red cut out; that is, of the complementary color, green.

317. Mixing Pigments. — Draw a broad line on the blackboard with a yellow crayon. Over this draw a similar band with a blue crayon. The result will be a band distinctly green.

The yellow crayon reflects green light as well as yellow, and absorbs all the other colors. The blue crayon reflects green light along with the blue, absorbing all the others. Hence, in superposing the two chalk marks, the mixture absorbs all but the green. The mark on the board is green, because that is the only color that survives the double absorption. In mixing pigments, the resulting color is the residue of a process of successive absorptions. If the spectral *colors*, blue and yellow, are mixed, the product is white instead of green. So we see that a mixture of colored lights is a very different thing from a mixture of pigments.

IX. INTERFERENCE AND DIFFRACTION

318. Newton's Rings. — Press together at their center two small pieces of heavy plate glass, using a small iron clamp for the purpose. Then look obliquely at the glass; curved bands of color may be seen surrounding the point of greatest pressure.

This experiment is like one performed by Newton while attempting to determine the relation between the colors in the soap bubble and the thickness of the film. He used a plano-convex lens of long focus resting on a plate of plane glass. Figure 299 shows a section of the apparatus. Between the lens and the plate there is a wedge-shaped film of air, very thin, and quite similar to that formed between the glass plates in the above experiment. If the glasses are viewed by reflected light, there is a dark spot at the point of contact, surrounded by several colored rings (Fig. 300); but if viewed by transmitted light, the colors are complementary to those seen by reflection (§ 316).

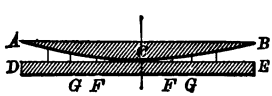


FIGURE 299. — NEWTONS RINGS.

The explanation is to be found in the interference of two sets of waves, one reflected internally from the curved surface *ACB*, and the other from the surface *DCE*, on which it presses. If light of one color is incident on *AB*, a portion will be reflected from *ACB*, and another portion from *DCE*. Since the light reflected from *DCE* has traveled farther by twice the thickness of the air film than that from *ACB*, and the film gradually increases in thickness from *C* outward, it follows that at some places the two reflected portions will meet in like phase, and at others in opposite phase, causing a strengthening of the light at the former, and extinction of it at the latter.

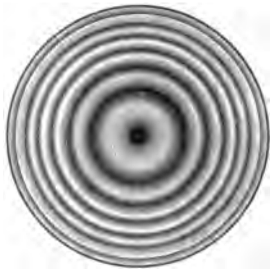


FIGURE 300. — COLORED RINGS.

If red light be used, the appearance will be that of a series of concentric circular red bands separated by dark ones, each shading off into the other. If violet light be employed, the colored bands will be closer together on account of the shorter wave length. Other colors will give bands intermediate in diameter between the red and violet. From this it follows that if the glasses be illuminated by white light, at every point some one color will be destroyed. The other colors will be either weakened or strengthened, depending on the thickness of the air film at the point under consideration, the color at each point being the result of mixing a large number of colors in unequal proportions. Hence, the point *C* will be surrounded by a series of colored bands.[1]

[1] The light from *ACB* differs in phase half a wave length from that reflected from *DE*, because the former is reflected in an optically dense

The colors of the soap bubble, of oil on water, of heated metals which easily oxidize, of a thin film of varnish, and of the surface of very old glass, are all caused by the interference of light reflected from the two surfaces of a very thin film.

319. Diffraction. — Place two superposed pieces of perforated cardboard in front of the condenser of the projection lantern. The projected images of the very small holes, as one piece is moved across the other, are fringed with the spectral colors.

With a fine diamond point rule a number of equidistant parallel lines very close together on glass. They compose a transparent *diffraction grating*. Substitute this for the prism in projecting the spectrum of sunlight or of the arc light on the screen (§ 300). There will be seen on the screen a central image of the slit, and on either side of it a series of spectra. Cover half of the length of the slit with red glass and the other half with blue. There will now be a series of red images and also a series of blue ones, the red ones being farther apart than the blue. Lines ruled close together on smoked glass may be used instead of a "grating."

These experiments illustrate a phenomenon known as *diffraction*. The colored bands are caused by the interference of the waves of light which are propagated in all directions from the fine openings. The effects are visible because the transparent spaces are so small that the intensity of the direct light from the source is largely reduced. Diffraction gratings are also made to operate by reflecting light. Striated surfaces, like mother-of-pearl, changeable silk, and the plumage of many birds, owe their beautiful changing colors to interference of light by diffraction.

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medium next to a rare one, and the latter in an optically rare medium next to a dense one. This phase difference is additional to the one above described.

Questions

1. How many degrees is it from the sun to the highest point of the primary rainbow?

2. Why is the red on the outside of the primary bow and on the inside of the secondary bow?

3. If there are but three primary sensations, red, green, and violet, what effect would it have on a person's vision if the nerves for red sensations were inoperative?

4. Why is the secondary rainbow less bright than the primary bow?

5. Are the two images of an object as formed on the retina of the two eyes identical? Explain.

6. Account for the crossed bands of light seen by looking through the wire screening of the window at the full moon.

7. Account for the change in color of aniline purple when viewed by the light of a common kerosene lamp.

8. Under what conditions could a rainbow be seen at midday?

9. Account for the colors on water when gasoline is poured on it.

10. Why does each person in using a microscope have to focus for his own eyes?

CHAPTER IX

HEAT

I. HEAT AND TEMPERATURE

320. Nature of Heat. — For a long time it was believed that heat was a subtle and weightless fluid that entered bodies and possibly combined with them. This fluid was called *caloric*. About the beginning of the last century some experiments of Count Rumford in boring brass cannon, and those of Sir Humphry Davy in melting two pieces of ice at freezing temperature by the friction of one piece on the other demonstrated that the caloric theory of heat was no longer tenable; and finally about the middle of the century, when Joule proved that a definite amount of mechanical work is equivalent to a definite amount of heat, it became evident that *heat is a form of molecular energy*.

The modern *kinetic* theory, briefly stated, is as follows: The molecules of a body have a certain amount of independent motion, generally very irregular. Any increase in the energy of this motion shows itself in additional warmth, and any decrease by the cooling of the body. The heating or the cooling of a body, by whatever process, is but the transference or the transformation of energy.

321. Temperature. — If we place a mass of hot iron in contact with a mass of cold iron, the latter becomes warmer and the former cooler, the heat flowing from the hot body

to the cold one. The two bodies are said to differ in *temperature* or "heat level," and when they are brought in contact there is a flow of heat from the one of higher temperature to the one of lower until thermal (heat) equilibrium is established.

Temperature is the thermal condition of a body which determines the transfer of heat between it and any body in contact with it. This transfer is always from the body of higher temperature to the one of lower. Temperature is a measure of the degree of hotness; it depends solely on the kinetic energy of the molecules of the body.

Temperature must be distinguished from quantity of heat. The water in a pint cup may be at a much higher temperature than the water in a lake, yet the latter contains a vastly greater quantity of heat, owing to the greater quantity of water.

322. Measuring Temperature. — Fill three basins with moderately hot water, cold water, and tepid water respectively. Hold one hand in the first, and the other in the second for a short time; then transfer both quickly to the tepid water. It will feel cold to the hand that has been in hot water and warm to the other. Hold the hand successively against a number of the various objects in the room, at about the same height from the floor. Metal, slate, or stone objects will feel colder than those of wood, even when side by side and of the same temperature.

These experiments show that the sense of touch does not give accurate information regarding the relative temperature of bodies, and some other method must be resorted to for reliable measurement. The one most extensively used is based on the regular increase in the volume of a body attending a rise in its temperature. This method is illustrated by the common mercurial thermometer.

II. THE THERMOMETER

323. The Thermometer. — The common *mercurial thermometer* consists of a capillary glass tube of uniform bore, on one end of which is blown a bulb, either spherical or cylindrical (Fig. 301). Part of the air is expelled by heating, and while in this condition the open end of the tube is dipped into a vessel of pure mercury. As the tube cools, mercury is forced into the tube by atmospheric pressure. Enough mercury is introduced to fill the bulb and part of the tube at the lowest temperature which the thermometer is designed to measure. Heat is now applied to the bulb until the expanded mercury fills the tube; the end is then closed in the blowpipe flame. The mercury contracts as it cools, leaving the larger portion of the capillary empty.

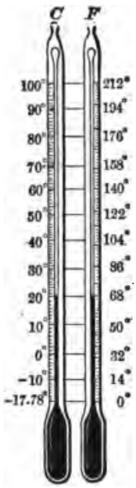


FIGURE 301. — C. AND F. THERMOMETERS.

324. The Necessity of Fixed Points. — No two thermometers are likely to have bulbs and stems of the same capacity. Consequently, the same increase of temperature will not produce equal changes in the length of the thread of mercury. If, then, the same scale were attached to all thermometers, their indications would differ so widely that the results would be worthless. Hence, if thermometers are to be compared, corresponding divisions on the scale of different instruments must indicate the same temperature. This may be done by graduating every thermometer by comparison with a standard, an expensive proceeding and for many purposes unnecessary, since mercury has a nearly uniform rate of expansion. If two

points are marked on the stem, the others can be obtained by dividing the space between them into the proper number of equal parts. Investigations have made it certain that under a constant pressure the temperature of *melting ice* and that of *steam* are invariable. Hence, the *temperature of melting ice* and *that of steam* under a pressure of 76 cm. of mercury (one atmosphere) have been chosen as the fixed points on a thermometer.

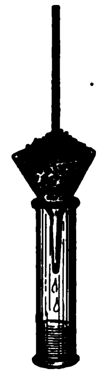


FIGURE 302. — FREEZING POINT.

325. Marking the Fixed Points. — The thermometer is packed in finely broken ice, as far up the stem as the mercury extends. The containing vessel (Fig. 302) has an opening at the bottom to let the water run out. After standing in the ice for several minutes the top of the thread of mercury is marked on the stem. This is called the *freezing point*.

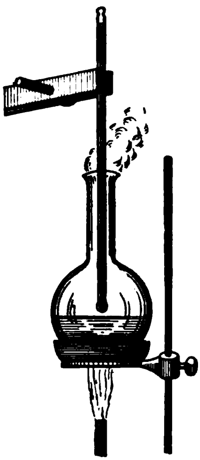


FIGURE 303. — MARKING THE BOILING POINT.

The *boiling point* is marked by observing the top of the mercurial column when the bulb and stem are enveloped in steam (Fig. 303) under an atmospheric pressure of 76 cm. (29.92 in.). If the pressure at the time is not 76 cm., then a correction must be applied, the amount being determined by the approximate rule that the temperature of steam rises 0.1° C. for every increase of 2.71 mm. in the barometric reading, near 100° C.

326. Thermometer Scales. — The distance between the fixed points is divided into equal parts called *degrees*. The number of such parts is wholly arbitrary, and several different scales have been

introduced. The number of thermometer scales in use in the eighteenth century was at least nineteen. Fortunately all but three of them have passed into ancient history.

The *Fahrenheit* scale, which is in general use in English-speaking countries, appears to have made its first appearance about 1714, but the earliest published description of it was in 1724. At that time this scale began at 0° and ended at 96°. Fahrenheit describes his scale as determined by three points: the lowest was the 0° and was found by a mixture of ice, water, and sea salt; the next was the 32° point and was found by dipping the thermometer into a mixture of ice and water without salt; the third was marked 96°, the point to which alcohol expanded "if the thermometer be held in the mouth or armpit of a healthy person." When this scale was extended, the boiling point was found to be 212°. The space between the freezing and the boiling point is therefore 180°.

The *Centigrade* scale was introduced by Celsius, professor of astronomy in the University of Upsala, about 1742. It differs from the Fahrenheit in making the freezing point 0° and the boiling point 100°, the space between being divided into 100 equal parts or degrees. The simplicity of Celsius's division of the scale has led to its general adoption in all countries for scientific purposes, and in many for domestic and industrial use.

The scale in both thermometers is extended beyond the fixed points as far as desired. The divisions below 0° are read as minus and are marked with the negative sign. The initial letters F. and C. denote the Fahrenheit and Centigrade scales respectively.

327. The Two Scales Compared. — In Fig. 304 *AB* is a thermometer with two scales attached, *P* is the head

of the mercury column, and F and C are the readings on the scales respectively. On the Fahrenheit scale, $AB = 180$ and $AP = F - 32$, since the zero is 32 spaces below A; on the Centigrade, $AB = 100$ and $AP = C$. Then the ratio of AP to AB is $\frac{F-32}{180} = \frac{C}{100}$.

FIGURE 304. — SCALES COMPARED.

By substituting the reading on either scale in this equation the equivalent on the other scale is easily obtained. For example, if it is required to express 68° F. on the Centigrade scale, then $\frac{68-32}{180} = \frac{C}{100}$; whence $C = 20°$.

328. Limitations of the Mercurial Thermometer. — As mercury freezes at − 38.8° C., it cannot be used as the thermometric substance below this temperature. For temperatures below − 38° C. alcohol is substituted for mercury. Under a pressure of one atmosphere mercury boils at about 350° C. For temperatures approaching this value and up to about 550° C. the. thermometer stem is filled with pure nitrogen under pressure. The pressure of the gas keeps the mercury from boiling (§ 356).

329. The Clinical Thermometer. — The clinical thermometer is a sensitive instrument of short range for indicating the temperature of the human body. It is usually graduated from 95° to 110° F., or from 35° to 45° C. There is a constriction in the tube just above the bulb (Fig. 305), which causes the thread of mercury to break at that point when the temperature begins to fall, leaving the


FIGURE 305. — CLINICAL THERMOMETER.

top of the separated thread to mark the highest temperature registered. A sudden jerk or tapping of the thermometer forces the mercury down past the constriction and sets it for a new reading. The normal temperature of the human body is 98.6° F. or 37° C.

Questions and Problems

1. Why do the degree spaces differ in length on different thermometers of the same scale?

2. What advantages does a thermometer with a cylindrical bulb have over one with a spherical bulb?

3. Why is mercury preferable to other liquids for use in thermometers?

4. Why is it necessary to have fixed points in thermometers?

5. The bulb of a thermometer generally contracts a little after the thermometer is completed. What is the result on the readings?

6. Why is nitrogen used in preference to oxygen in thermometers for high temperatures?

7. Why should the thermometer tube be of uniform bore?

8. Express in Fahrenheit degrees the following 4° C., 30° C., – 38° C.

9. Express in Centigrade degrees the following 39° F., – 40° F., 68° F.

10. The fixed points on a Centigrade thermometer were found to be incorrect; the freezing point read 2° and the boiling point 99°. When this thermometer was immersed in a liquid the reading was 50°. What was the correct temperature of the liquid?

(NOTE. — Compare this incorrect thermometer with a correct one just as a Fahrenheit thermometer is compared with a Centigrade in § 327.)

11. A thermometer read 40° C. in a water bath. When tested it was found to read 0° at the freezing point, but 95° instead of 100° at the boiling point. What was the correct temperature of the bath?

12. If a Fahrenheit thermometer read 210° in steam and 31° in melting ice, what would it read as the equivalent of 70° F.?

13. A correct Fahrenheit thermometer read 70° as the temperature of a room. An incorrect Centigrade thermometer read 20° in the same room. What was the error of the latter?

14. A certain Centigrade thermometer reads 2° in melting ice and 100° in steam under normal atmospheric pressure. What is the correct value for a reading of 25° on this thermometer?

III. EXPANSION

330. Expansion of Solids. — Insert a long knitting needle *A* in a block of wood so as to stand vertically (Fig. 306). A second needle *D* is supported parallel to the first by means of a piece of cork or wood *C*. The lower end of *D* just touches the mercury in the cup *H*. An electric circuit is made through the mercury, the needle, an electric battery, and the bell *B*, as shown. Now apply a Bunsen flame to *A*; *D* will be lifted out of the mercury and the bell will stop ringing. Then heat *D* or cool *A*, and the contact of *D* with the mercury will be renewed as shown by the ringing of the bell.

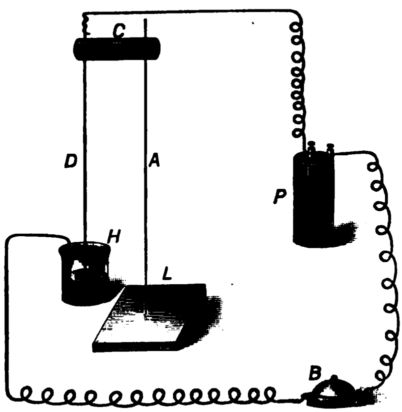


FIGURE 306. — SHOWING EXPANSION.

This experiment shows that solids expand in length when heated and contract when cooled. To this rule of expansion there are a few exceptions, notably iodide of silver and stretched india-rubber.

Rivet together at short intervals a strip of sheet copper and one of sheet iron *D* (Fig. 307). Support this compound bar so as to play between two points *A* and *C*, which are connected through the battery *P* and the bell *B*. Apply a Bunsen flame to the bar. It will warp,

throwing the top over against either *A* or *C*, and will cause the bell to ring.

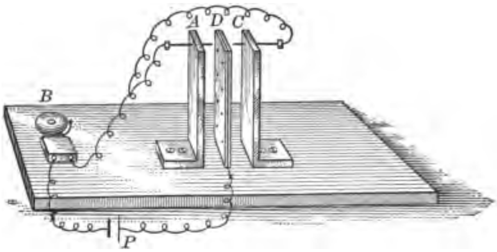


FIGURE 307. — UNEQUAL EXPANSION.

The experiment shows that the two metals expand unequally and cause the bar to warp.

FIGURE 308. — EXPANSION OF BALL.

Figure 308 illustrates a piece of apparatus known as Gravesande's ring. It consists of a metallic ball that at ordinary temperatures will just pass through the ring. Heat the ball in boiling water. It will now rest on the ring and will not fall through until it has cooled.

We conclude that the expansion of a solid takes place in every direction.

331. Expansion of Liquids. — Select two four-inch test tubes, fit to each a perforated stopper, through which passes a small glass tube about six inches long. The capacity of the two test tubes after stoppers are inserted should be equal. Fill one tube with mercury and the other with glycerine colored with an aniline dye. Set the test tubes in a beaker of water over a Bunsen flame (Fig. 309) and note the change in the height of the liquids in the tubes.

FIGURE 309. — EXPANSION OF LIQUIDS.

Two facts are illustrated: first, liquids are affected by heat in the same way as

solids; second, the expansion of the liquids is greater than that of the glass or there would be no apparent increase in their volume.

Some liquids do not expand when heated at certain points on the thermometric scale. Water, for example, on heating from 0° C. to 4° C. contracts, but above 4° C. it expands.

332. Expansion of Gases. — Fit a bent delivery tube to a small Florence flask (Fig. 310). Fill the flask with air and place the upturned end of a delivery tube under an inverted graduated glass cylinder filled with water. Heat the flask by immersing it in a vessel of moderately hot water. The air will expand and escape through the delivery tube into the cylinder; note the amount. Now refill the flask with some other gas, as coal gas, and repeat the experiment. The amount of gas collected will be nearly the same.

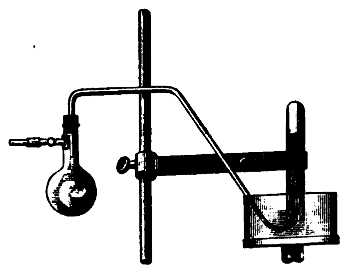


FIGURE 310. — EXPANSION OF GASES.

Investigation has shown that all gases which are hard to liquefy expand very nearly alike at atmospheric pressure, approaching equality as the pressure is diminished. Gases that are easily liquefied, as carbon dioxide, show the largest variation in the expansion.

333. Coefficient of Linear Expansion. — Nearly all solids expand with increase of temperature, but they do not expand equally. Assume three rods of the same length, — zinc, brass, and steel. With the same rise of temperature, the zinc rod will increase in length 50 per cent more than the brass, and the brass nearly 50 per cent more than the steel. A brass bar will expand in length 20 times as much as a bar of "invar" (nickel steel) if the bars are

of the same length and undergo the same change of temperature.

The *coefficient of linear expansion*, or expansion in length, expresses this property of expansion in a numerical way. *It is the increase in a unit length of a substance per degree increase in temperature.* This is equivalent to the expression:

$$\textit{Coefficient of linear expansion} = \frac{\textit{increase in length}}{\textit{original length} \times \textit{temp. change}}.$$

If l_1 and l_2 denote the lengths of a metallic rod at temperatures t_1 and t_2 respectively, then $\frac{l_2 - l_1}{t_2 - t_1} = \frac{l_2 - l_1}{t}$ is the whole expansion for 1°; t is the difference of temperature. If a denotes the coefficient of expansion, then $a = \frac{l_2 - l_1}{l_1 t}$; whence $l_2 = l_1(1 + at)$.

Since this coefficient is a ratio, it makes no difference what unit of length is used. Coefficients of expansion are usually given in terms of the Centigrade degree. For the Fahrenheit degree the coefficient is, of course, $\frac{5}{9}$ as great as for the Centigrade.

Some Coefficients of Linear Expansion

Invar	0.0000009	Copper	0.0000172
Glass	0.0000086	Brass	0.0000188
Platinum	0.0000088	Silver	0.0000191
Cast Iron	0.0000113	Tin	0.0000217
Steel	0.0000132	Zinc	0.0000294

334. Illustrations of Linear Expansion. — Many familiar facts are accounted for by expansion or contraction attending changes of temperature. If hot water is poured into a thick glass tumbler, the glass will probably crack by reason of the stress produced by the

Bridge over the Firth of Forth.

Allowance for the expansion and contraction of the steel must be made in the construction.

sudden expansion of its inner surface. On the other hand, crucibles and other laboratory utensils are now made of clear *fused* quartz; fused quartz has so small a coefficient of expansion that a red-hot crucible may be plunged into water without cracking. The coefficients of glass and platinum are so nearly equal that platinum wires may be sealed into glass without cracking the latter when it cools.

Crystalline rocks, on account of unequal expansion in different directions, are slowly disintegrated by changes of temperature; and for the same reason quartz crystals, when strongly heated, fly in pieces. The outcropping granite hills of the celebrated South African Matopos have been broken into huge boulders and irregular masses by the large expansion in the fervid heat of midday and the subsequent rapid contraction during the low temperature of the succeeding night.

In long steel bridges built in cold climates considerable expansion occurs in summer, and a certain freedom of motion of the parts must be provided for. Long suspension bridges are several inches higher at the middle in midwinter than in the heat of summer. Long steam pipes are fitted with expansion joints to permit one part to slide into the other; bends or elbows in the pipe are also used, so that the pipe may accommodate itself to the expansion.

335. Compensated Clocks and Watches. — If the length of a pendulum changes with temperature, the period of vibration will also change and the clock will not have a constant rate. The balance wheel of a watch serves a similar purpose of regulating the period of vibration and is similarly affected by changes in temperature. To compensate for these changes so as to keep the period of vibration constant, the principle of unequal expansion is employed.

FIGURE 311. — MERCURIAL PENDULUM.

The bob of a compensated mercurial pendulum consists of one or more glass jars, nearly filled with mercury, and attached to the lower end of a steel rod (Fig. 311). A rise of temperature lengthens the rod and lowers the center of oscillation; but the mercury expands upward and compensates by raising the center of oscillation. By a proper adjustment of the quantity of mercury in the tubes, its expansion may be made to compensate for that of the rod.

The rate of a watch depends largely on the balance wheel. Unless this is compensated, it expands when the temperature rises and the watch loses time, the larger wheel oscillating more slowly under the force supplied by the elasticity of the hairspring. Compensation is secured by making the rim of the wheel in two sections, each being made of two materials and supported by one end on a separate arm (Fig. 312). The more expansible metal is on the outside. When the temperature rises and the radial arms expand, the loaded free ends a, a' of the sections move inward, thus compensating for the increased length of the radial arms. The final adjustment is made by screwing in or out the studs on the rim.

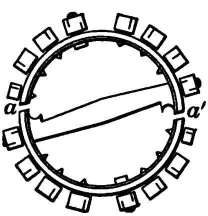


FIGURE 312.—COMPENSATED BALANCE WHEEL.

336. Cubical Expansion. — In general, solids and liquids when heated expand in all directions with increase of volume. This expansion in volume is called *cubical expansion. The coefficient of cubical expansion is the increase in volume of a unit volume per degree rise of temperature.*

Precisely as in the case of linear expansion, the coefficient of cubical expansion k may be expressed by the equation

$$k = \frac{v_2 - v_1}{v_1 t}.$$

Whence $$v_2 = v_1(1 + kt).$$

The coefficient of cubical expansion of a substance is three times its coefficient of linear expansion. Thus if the coefficient of linear expansion of cast iron is 0.0000113, its coefficient of cubical expansion is 0.0000339.

337. Expansion of Water. — Water exhibits the remarkable property of contracting when heated at the freezing point. This contraction continues up to 4° C., when expansion sets in. The greatest density of water is therefore at 4° C., and its density at 6° is nearly the same as at 2°.

In a lake or pond water at 4° sinks to the bottom, while water below 4° is lighter and rises to the top, where the freezing begins. Ice forms at the surface of a body of cold water, which freezes from the surface downwards. Fishes are thus protected from freezing.

338. Law of Charles. — It was shown by Charles, in 1787, that *the volume of a given mass of any gas under constant pressure increases by a constant fraction of its volume at zero for each rise of temperature of* 1° C. The investigations of Regnault and others show that the law is not rigorously true, and that the accuracy of Charles's law is about the same as that of Boyle's law. The coefficient of expansion k of dry air is 0.003665, or about $\frac{1}{273}$. This fraction may be considered as the coefficient of expansion of any true gas.

339. The Absolute Scale. — The law of Charles leads to a scale of temperature called the *absolute scale.* By this law the volumes of any mass of gas, under constant pressure, at 0° C., and at any other temperature t° C., are connected by the following relations (§ 336):

$$v = v_0(1 + \tfrac{1}{273}t) = \frac{v_0(273 + t)}{273} \quad . \quad . \quad . \quad (a)$$

At any other temperature, t', the volume becomes

$$v' = \frac{v_0(273 + t')}{273} \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

Divide (a) by (b) and

$$\frac{v}{v'} = \frac{273 + t}{273 + t'}.$$

Suppose now a new scale is taken, whose zero is 273 Centigrade divisions below the freezing point of water,

and that temperatures on this scale are denoted by T. Then $273 + t$ will be represented by T, and $273 + t'$ by T', and

$$\frac{v}{v'} = \frac{273 + t}{273 + t'} = \frac{T}{T'},$$

or *the volumes of the same mass of gas under constant pressure are proportional to the temperatures on this new scale.* The point 273° below 0° C. is called the *absolute zero*, and the temperatures on this scale, *absolute temperatures.* Up to the present it has not been found possible to cool a body to the absolute zero; but by evaporating liquid hydrogen under very low pressure, a temperature estimated to be within 9° of the absolute zero has been obtained by Professor Dewar; and Professor Onnes, by liquefying helium, believes that he obtained a temperature within 2° or 3° of the absolute zero.

At these low temperatures steel and rubber become as brittle as glass.

340. The Gas Equation. — The laws of Boyle and Charles may be combined into one expression, which is known as *the gas equation.* It has a wider application even than its method of derivation would indicate.

Let v_0, p_0, T_0 be the volume, pressure, and absolute temperature of a given mass of gas.

Also let v, p, T be the corresponding quantities for the same mass of gas at pressure p and temperature T.

Then applying Boyle's law (§ 87) to increase the pressure to the value p, the temperature remaining constant, we have

$$\frac{v_0}{v'} = \frac{p}{p_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

where v' is the new volume corresponding to the pressure p.

Next apply the law of Charles (§ 339), keeping the pressure constant at the value p, and starting with the new volume v'. Then since the volumes are directly proportional to the temperatures, we have

$$\frac{v'}{v} = \frac{T_0}{T}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

where v is the new volume corresponding to temperature T.

Multiply (a) and (b) together member by member, and $\frac{v_0}{v} = \frac{pT_0}{p_0T}$, or $\frac{p_0v_0}{T_0} = \frac{pv}{T}$ = a constant, since p and T are any pressure and temperature and v corresponds. This constant is usually denoted by R. We may therefore write

$$pv = RT. \quad . \quad . \quad . \quad \text{(Equation 33)}$$

To illustrate the use of the above relation: If 20 cm.³ of gas at 20° C. is under a pressure of 76 cm. of mercury, what will be the pressure when its volume is 30 cm.³ and temperature 50° C.?

From equation (33), $\frac{pv}{T}$ is a constant,

or
$$\frac{pv}{T} = \frac{p'v'}{T'}.$$

Hence
$$\frac{76 \times 20}{273 + 20} = \frac{p \times 30}{273 + 50},$$

from which
$$p = 55.85 \text{ cm.}$$

Questions and Problems

1. Telegraph wires often "hum" in the wind. Why is the pitch higher in winter than in summer?

2. When a piece of ice floats, about $\frac{1}{10}$ of its volume projects out of the water. If a pan is level full of water and a piece of ice floats in it, both at 0° C., why is there no change of level when the ice melts?

3. Why is a fountain pen more likely to leak when nearly empty?

4. If the bulb of a mercurial thermometer is plunged into hot water, the top of the thread of mercury first falls and then rises. Explain.

5. A copper rod 125 cm. long at 0° C. expands to 125.209 cm. at 100° C. Find the coefficient of linear expansion of copper.

6. The coefficient of linear expansion of steel is 0.0000132. What will be the variation in length of a steel bridge 250 ft. long between the temperatures – 10° C. and 40° C.?

7. The coefficient of linear expansion of steel is 0.0000132 and that of zinc is 0.0000294. What relative lengths of rods of these metals will have equal expansions in length for the same changes of temperature?

8. The coefficient of the volume expansion of glass is 0.000258. A density bottle at 15° C. holds 25 $cm.^3$. What will be its capacity at 25° C.?

9. Why should the reading of the mercurial barometer be corrected for temperature? If the relative volume coefficient of expansion of mercury in glass is 0.000155, and the barometer reads 755 mm. at 20° C., what would be the reduced reading at 0° C.?

10. The volume of a given mass of gas at 740 mm. pressure is 1200 $cm.^3$; find its volume at 760 mm.

11. The mass of a liter of air at 0° C. and 76 cm. pressure is 1.3 g. Find the mass of 10 liters of air at 20° C. and 74 cm. pressure.

12. A liter of hydrogen at 15° C. is heated at constant pressure to 75° C. Find its volume.

13. A quantity of gas is collected in a graduated tube over mercury. The reading of the mercury level in the tube is 20 cm., the volume of the gas is 60 $cm.^3$, the temperature is 20° C., and the barometer reading is 74 cm. How many cubic centimeters of gas are there at 0° C. and 76 cm. pressure?

14. Three cubic centimeters of air are introduced into the vacuum of a mercurial barometer. The barometer read 76 cm. before introducing the air and 57 cm. after. What volume does the air occupy in the barometer?

IV. MEASUREMENT OF HEAT

341. The Unit of Heat. — The unit of heat in the *c. g. s.* system is the *calorie.* It is defined as *the quantity of heat that will raise the temperature of one gram of water one degree Centigrade.* There is no agreement as to the position of the one degree on the thermometric scale, although it is known that the unit quantity of heat varies slightly at different points on the scale. If the degree interval chosen is from 15° to 16° C., the calorie is then the one hundredth part of the heat required to raise the temperature of one gram of water from 0° to 100° C.

In engineering practice in England and America the British thermal unit (B. T. U.) is commonly employed. It is *the heat required to raise the temperature of one pound of water one degree Fahrenheit.*

342. Thermal Capacity. — The *thermal capacity* of a body is the number of calories required to raise its temperature one degree Centigrade. The thermal capacity of equal masses of different substances differs widely. For example, if 100 g. of water at 0° C. be mixed with 100 g. at 100° C., the temperature of the whole will be very nearly 50° C. But if 100 g. of copper at 100° C. be cooled in 100 g. of water at 0° C., the final temperature will be about 9.1° C. The heat lost by the copper in cooling through 90.9° is sufficient to heat the same mass of water only 9.1°, that is, the thermal capacity of water is about ten times as great as that of an equal mass of copper.

343. Specific Heat. — The *specific heat* of a substance is the number of calories of heat required to raise the temperature of *one gram* of it through one degree Centigrade. It may be defined independently of any temperature scale as the ratio between the number of units of heat required

to raise the temperature of equal masses of the substance and of water through one degree. The specific heat of mercury is 0.033, that is, the heat that will raise 1 g. of mercury through 1° C. will raise 1 g. of water through only 0.033° C.

The specific heat of water is twice as great as that of ice (0.505), and more than twice as great as that of steam under constant pressure (0.477).

344. Numerical Problem in Specific Heat. — The principle applied in the solution of such problems is that the gain or loss of heat by the water is equal to the loss or gain of heat by the body introduced into the water. The gain or loss of heat by the body is equal to the product of its mass, its specific heat, and its change of temperature.

To illustrate: 20 g. of iron at 98° C. are placed in 75 g. of water at 10° C. contained in a copper beaker weighing 15 g., specific heat 0.095. The resulting temperature of the water and the iron is 12.5° C. Find the specific heat of iron.

The thermal capacity of the beaker is $15 \times 0.095 = 1.425$ calories. The heat lost by the iron is $20 \times s \times (98 - 12.5)$ calories, in which s represents the specific heat of iron, and $(98 - 12.5)$ its change of temperature. The heat gained by the water and the copper vessel is $(75 + 1.425) \times (12.5 - 10)$ calories; the second factor is the gain in temperature of the water and the beaker. It follows by equating these two quantities that $20 \times s \times (98 - 12.5) = (75 + 1.425) \times (12.5 - 10)$. Solving for s, we have $s = 0.112$ calorie per gram.

Questions and Problems

1. What is the specific heat of water?

2. A pound of water and a pound of lead are subjected to the same source of heat for 10 min. Which will be at the higher temperature?

3. If equal quantities of heat are applied to equal masses of iron and lead, which will show the greater change of temperature?

4. Equal balls of iron and zinc are heated in boiling water and are placed on a cake of beeswax. Which will melt the further into the wax?

5. Why is water better than any other liquid for heating purposes?

6. Why is a rubber bag filled with hot water better for a foot warmer than an equal mass of any solid?

7. A copper beaker has a mass of 25 g. The specific heat of copper is 0.095. What is the thermal capacity of the beaker?

8. How much heat will it take to raise a liter of water from 20° C. to 100° C.?

9. The specific heat of iron is 0.112. How much heat will be required to raise 250 g. of iron from 10° to 45° C.?

10. 120 g. of water at 5° C. are mixed with 200 g. of water at 50° C. Assuming that no heat is lost, what will be the resulting temperature?

11. 89.2 g. of iron at 90° C. are placed in 70 g. of water at 10° C.; the resulting temperature is 20° C. Find the specific heat of iron.

12. A copper ball weighing 1 kg. has a specific heat of 0.095. It is heated in a furnace to the temperature of the furnace and dropped into a liter of water at 10° C. The temperature of the water rises to 93.1° C. Find the temperature of the furnace.

13. How many calories in the British Thermal Unit?

14. A glass beaker weighs 100 g. If the specific heat of the glass is 0.177, how much water will have the same thermal capacity as the beaker?

15. Why do islands in the sea have smaller extremes of temperature than inland areas?

V. CHANGE OF STATE

345. The Melting Point. — A body is said to *melt* or *fuse* when it changes from the solid to the liquid state by the application of heat. The change is called *melting*, *fusion*, or *liquefaction*. The temperature at which fusion takes place is called the *melting point*. Solidification or freezing is the converse of fusion, and the temperature of solidification is usually the same as the melting point of the same substance. Water, if undisturbed, may be cooled a number of degrees below 0° C., but if it is disturbed it

usually freezes at once, and its temperature rises to the freezing point.

The melting point of crystalline bodies is well marked. A mixture of ice and water in any relative proportion will remain without change if the temperature of the room is 0° C.; but if the temperature is above zero, some of the ice will melt; if it is below zero, some of the water will freeze. Some substances, like wax, glass, and wrought iron, have no sharply defined melting point. They first soften and then pass more or less slowly into the condition of a viscous liquid. It is this property which permits of the bending and molding of glass, and the rolling, welding, and forging of iron.

346. Change in Volume accompanying Fusion. — Fit to a small bottle a perforated stopper through which passes a fine glass tube. Fill with water recently boiled to expel the air, the water extending halfway up the tube. Pack the apparatus in a mixture of salt and finely broken ice. The water column at first will fall slowly, but in a few minutes it will begin to rise, and will continue to do so until water flows out of the top of the tube. The water in the bottle freezes, expands, and causes the overflow.

Most substances occupy a larger volume in the liquid state than in the solid; that is, they expand in liquefying. A few substances, like water and bismuth, expand in solidifying. When water freezes, its volume increases 9 per cent. If this expansion is resisted, water in freezing is capable of exerting a force of about 2000 kg. per square centimeter. This explains the bursting of water pipes when the water in them freezes, and the rending of rocks by the freezing of water in cracks and crevices. The expansion of cast iron and type metal when they solidify accounts for the exact reproduction of the mold in which they are cast.

347. Effect of Pressure on the Melting Point. — Support a rectangular block or prism of ice on a stout bar of wood. Pass a thin iron wire around the ice and the bar of wood, and suspend on it a weight of 25 to 50 lb. The pressure of the wire lowers the melting point of the ice immediately under it and the ice melts; the water, after passing around the wire, where it is relieved of pressure, again freezes. In this way the wire passes slowly through the ice, leaving the block solidly frozen.

A rough numerical statement of the effect of pressure on the freezing point of water is that a pressure of one ton per square inch lowers the freezing point to $-1°$ C. Familiar examples of refreezing, or *regelation*, are the hardening of snowballs under the pressure of the hands, the formation of solid ice in a roadway where it is compressed by vehicles and the hoofs of horses, and frozen footforms in compact ice after the loose snow has melted around them. The ice of a glacier melts where it is under the enormous pressure of the descending masses above it. The melting permits the ice to accommodate itself to abrupt changes in the rocky channel, and a slow iceflow results. As soon as the pressure at any surface is relieved, the water again freezes (Fig. 313).

FIGURE 313. — MER DE GLACE, CHAMOUNIX.

348. Heat of Fusion. — When a solid melts, a quantity of heat disappears; and, conversely, when a liquid solidifies, the amount of heat generated is the same as dis-

appears during liquefaction. The *heat of fusion* of a substance is the number of calories required to melt a gram of it without change of temperature. The heat of fusion of ice is 80 calories.

As an illustration of the heat of fusion, place 200 g. of clean ice, broken into small pieces, into 500 g. of water at 60° C. When the ice has melted, the temperature will be about 20° C. The heat lost by the 500 g. of water equals $500 \times (60 - 20) = 20{,}000$ calories. This heat goes to melt the ice and to raise the resulting water from 0° C. to 20° C. To raise this water from 0° to 20° requires $200 \times 20 = 4000$ calories. The remainder, $20{,}000 - 4000 = 16{,}000$ calories, went to melt the ice. Then the heat of fusion of ice is $16{,}000 \div 200 = 80$ calories per gram.

349. Heat lost in Solution. — Fill a beaker partly full of water at the temperature of the room, and add some ammonium nitrate crystals. The temperature of the water will fall as the crystals dissolve.

This experiment illustrates the fact that heat disappears when a body passes from the solid to the liquid state by solution. The use of salt in soup or of sugar in tea absorbs heat. The heat energy is used to pull down the solid structure.

350. Freezing Mixtures. — Freezing mixtures are based on the absorption of heat necessary to give fluidity. Salt water freezes at a lower temperature than fresh water. When salt and snow or pounded ice are mixed together, both become fluid and absorb heat in the passage from the one state to the other. By this mixture a temperature of $-22°$ C. may be obtained. Still lower temperatures may be reached with other mixtures, notably with sulpho-cyanide of sodium and water.

351. Vaporization. — Pour a few drops of ether into a beaker and cover closely with a plate of glass. After a few seconds bring a lighted taper to the mouth of the beaker. A sudden flash will show that the vapor of ether was mixed with the air.

Support on an iron stand a Florence flask two-thirds full of water and apply heat. In a short time bubbles of steam will form at the bottom of the flask, rise through the water, and burst at the top, producing violent agitation throughout the mass.

Vaporization is the conversion of a substance into the gaseous form. If the change takes place slowly from the surface of a liquid, it is called *evaporation;* but if the liquid is visibly agitated by rapid internal evaporation, the process is called *ebullition* or *boiling.*

352. Sublimation. — When a substance passes directly from the solid to the gaseous form without passing through the intermediate state of a liquid, it is said to *sublime.* Arsenic, camphor, and iodine sublime at atmospheric pressure, but if the pressure be sufficiently increased, they may be fused. Ice also evaporates slowly even at a temperature below freezing. Frozen clothes dry in the air in freezing weather. At a pressure less than 4.6 mm. of mercury, ice is converted into vapor by heat without melting.

353. The Spheroidal State. — When a small quantity of liquid is placed on hot metal, as water on a red-hot stove, it assumes a globular or spheroidal form, and evaporates at a rate between ordinary evaporation and boiling. It is then in the *spheroidal state.* The vapor acts like a cushion and prevents actual contact between the liquid and the metal. The globular form is due to surface tension. Liquid oxygen at $-180°$ C. assumes the spheroidal form on water. The temperature of the water is relatively high compared with that of the liquid oxygen.

354. Cold by Evaporation. — Tie a piece of fine linen around the bulb of a thermometer and pour on it a few drops of sulphuric ether. The temperature will at once begin to fall, showing that the bulb has been cooled.

In the evaporation of ether, some of the heat of the thermometer is used to do work on the liquid.

Sprinkling the floor of a room cools the air, because of the heat expended in evaporating the water. Porous water vessels keep the water cool by the evaporation of the water from the outside surface. Liquid carbon dioxide is readily frozen by its own rapid evaporation. Dewar liquefied oxygen by means of the temperature obtained through the successive evaporation of liquid nitrous oxide and ethylene. Similarly, by the evaporation of liquid air he has liquefied hydrogen. The evaporation of liquid hydrogen under reduced pressure has

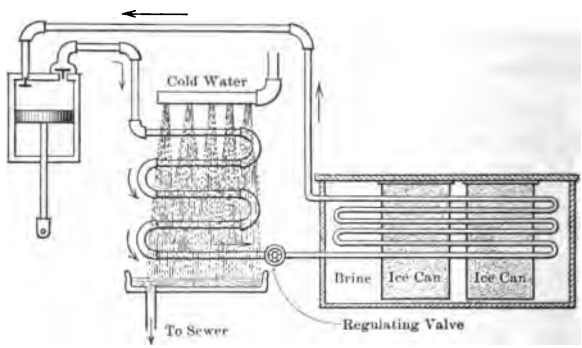


FIGURE 314. — ICE PLANT.

enabled him to obtain a temperature but little removed from the absolute zero, $-273°$ C. More recently Professor Onnes of Leyden, by the evaporation of liquid helium, has reached the extremely low temperature of $-271.3°$ C. or $1.7°$ absolute.

355. Ammonia Ice Plant. — The low temperature produced by the rapid evaporation of liquid ammonia is utilized in the manufacture of ice and for general cooling in refrigerator plants. Ammonia may be liquefied by pressure alone. At a temperature of 80° F. the

required pressure is 155 pounds per square inch. The essential parts of an ice plant are shown in Fig. 314. Gaseous ammonia is compressed by a pump in condenser pipes, over which flows cold water to remove the heat. From the condenser the liquid ammonia passes very slowly through a regulating valve into the pipes of the evaporator. The pressure in the evaporator is kept low by the pump, which acts as an exhaust pump on one side and as a compressor on the other. The pump removes the evaporated ammonia rapidly and the evaporation absorbs heat. The pipes in which the evaporation takes place are either in a tank of brine, or in the refrigerating room. Smaller tanks of distilled water are placed in the brine until the water in them is frozen. The pipes in the refrigerating room are covered with hoar frost, which is frozen moisture from the air. The temperature of the brine is reduced to about 16° to 18° F. The brine does not freeze at this temperature.

The process is continuous because the gaseous ammonia is returned to the condensing coils, which are cooled with water. It thus passes repeatedly through the same cycle of physical changes.

356. Effect of Pressure on the Boiling Point. — Place a flask of warm water under the receiver of an air pump. It will boil violently when the receiver is exhausted.

FIGURE 315. — BOILING UNDER REDUCED PRESSURE.

Fill a round-bottomed Florence flask half full of water and heat until it boils vigorously. Cork the flask, invert, and support it on a ring stand (Fig. 315). The boiling ceases, but is renewed by applying cold water to the flask. The cold water condenses the vapor, and reduces the pressure within the flask so that the boiling begins again.

The effect of pressure on the boiling point is seen in the low temperature of boiling water at high elevations, and in the high temperature of the water under pressure in digesters used for extracting gelatine from bones. The boiling point of water falls 1° C. for an increase in eleva-

tion of about 295 m. At Quito the boiling point is near 90° C.

357. Heat of Vaporization. — The *heat of vaporization* is the number of calories required to change one gram of a liquid at its boiling point into vapor at the same temperature. Water has the greatest heat of vaporization of all liquids. The most carefully conducted experiments show that the heat of vaporization of water under a pressure of one atmosphere is 536.6 calories per gram.

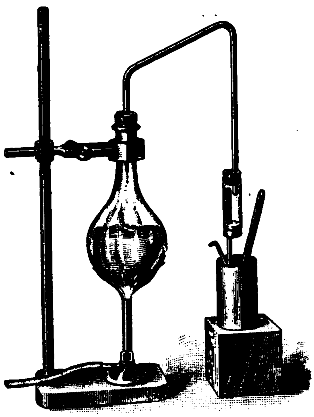


FIGURE 316. — HEAT OF EVAPORATION.

Set up apparatus like that shown in Fig. 316. The steam from the boiling water is conveyed into a beaker containing a known quantity of water at a known temperature. The increase in the mass of water gives the amount of steam condensed. The "trap" in the delivery tube catches the water that condenses before it reaches the beaker. Suppose that the experiment gave the following data: Amount of water in the beaker, 400 g. at the beginning, 414.1 g. at the end, including the thermal capacity of the beaker in terms of water; temperature at the beginning, 20° C., and at the end, 41° C.; observed boiling point, 99° C.; there were 14.1 g. of steam condensed. Now, by the principle that the heat lost or given off by the steam equals that gained by the water, we have

$$400 \times (41 - 20) = 14.1 \times l + 14.1 \times (99 - 41);$$

whence $l = 537.7$ cal. per gram.

358. Formation of Dew. — The presence of clouds and the "sweating" of pitchers filled with ice water show that the atmosphere contains water vapor. The amount of water

vapor that the atmosphere can hold in suspension depends on its temperature. After sunset, if the sky is clear, bodies on the earth's surface, such as grass, leaves, and roots, soon cool below the temperature of the surrounding air, and water in the form of *dew* collects on them. Clouds act as blankets and prevent the cooling off process, so that little or no dew collects. Wind promotes evaporation and dew fails to collect. If the temperature falls sufficiently low, the dew is deposited as frost.

359. The Dew Point. — *The dew point is the temperature at which the aqueous vapor of the atmosphere begins to condense.* If water at the temperature of the room be poured into a polished nickel-plated beaker and small pieces of ice be added with stirring, a mist will soon collect on the outside of the beaker. The temperature of the water is then the *dew point.*

360. Humidity. — The terms *dryness* and *moisture* applied to the air are purely relative. Usually the air is not saturated, that is, it does not contain all the water vapor it can hold. If it is near the saturation point, it is moist; if it is very far from saturation, it is dry. The *relative humidity* of the air is *the ratio between the amount of water vapor actually present and the amount that would be present if the air were saturated at the same temperature.* The air is saturated at the dew point. A dry day is one on which the dew point is much below the temperature of the air; a damp day is one on which the dew point is close to the temperature of the air. Humidity is expressed as a per cent of saturation.

361. Humidity and Health. — The humidity of the air has an important bearing on health. The dry air of a furnace-heated house promotes excessive evaporation from the bodies of the occupants, producing sensations of chil-

liness and discomfort. On the other hand, excessive humidity retards healthful evaporation, gives a sensation of depression, and in hot weather checks Nature's method of keeping cool by evaporation. The humidity conducive to health is about 50 per cent.

Questions and Problems

1. Why does a drop of alcohol on the hand feel cold?

2. Why does a shower in summer cool the air?

3. Why is there less dew on gravel than on the grass?

4. Why can blocks of ice be made to adhere by pressure?

5. Why do your eye glasses fog over when you go from the cold air outside into a warm room?

6. Water in a porous vessel standing in a current of air is colder than water in a glass pitcher. Why?

7. Why does warming a room make it feel dryer?

8. Why does water boil away faster on some days than on others?

9. Why does wind dry up the roads after a rain?

10. Why does moisture collect on the carburetor of a gasoline engine when it is in operation unless it is heated?

11. How much heat does it take to convert 50 g. of water at 100° C. into steam at 100° C.?

12. How much ice will 100 g. of water at 100° C. melt?

13. How much ice will 100 g. of steam at 100° C. melt?

14. 100 g. of ice and 20 g. of steam at 100° C. are put into a calorimeter. If no heat is lost, what will be the temperature of the water after all the ice is melted?

15. How much water at 80° C. will just melt a kilogram of ice?

16. How much steam will be required to raise the temperature of a kilogram of water from 20° to 50° C.?

17. How much ice will it take to cool a kilogram of water from 50° to 20° C.?

18. Mt. Washington is 6288 ft. above sea level; at what temperature does water boil on its top?

19. Water boils in the City of Mexico at 92.3° C. What is its elevation above the sea?

20. 50 g. of ice at 0° C. are put into 50 g. of water at 35° C. How much of the ice will melt?

VI. TRANSMISSION OF HEAT

362. Conduction. — Twist together two stout wires, iron and copper, of the same diameter, forming a fork with long parallel prongs

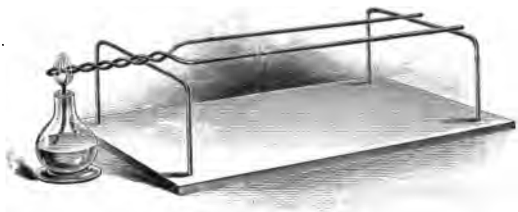


FIGURE 317. — DIFFERENCE IN CONDUCTIVITY.

and a short stem. Support them on a wire stand (Fig. 317), and heat the twisted ends. After several minutes find the point on each wire, farthest from the flame, where a sulphur match ignites when held against the wire. This point will be found farther along on the copper than on the iron, showing that the former has led the heat farther from its source.

Prepare a cylinder of uniform diameter, half of which is made of brass and half of wood. Hold a piece of writing paper firmly around the junction like a loop (Fig. 318). By applying a Bunsen flame the paper in contact with the wood is soon scorched, while the part in contact with the brass is scarcely injured. The metal conducts the heat away and keeps the temperature of the paper below the point of ignition. The wood is a poor conductor.

FIGURE 318. — CYLINDER HALF WOOD, HALF BRASS.

These experiments show that solids differ in their conductivity for heat. The metals are the best

conductors ; wood, leather, flannel, and organic substances in general are poor conductors ; so also are all bodies in a powdered state, owing doubtless to a lack of continuity in the material.

363. Conductivity of Liquids. — Pass a glass tube surmounted with a bulb through a cork fitted to the neck of a large funnel. Support the apparatus as shown in Fig. 319. The glass stem should stand in colored water. Heat the bulb slightly to expel some air, so that the liquid will rise in the tube. Fill the funnel with water, covering the bulb to the depth of about one centimeter. Pour a spoonful of ether on the water and set it on fire. The steadiness of the index shows that little if any of the heat due to the burning ether is conducted to the bulb.

FIGURE 319.—WATER POOR CONDUCTOR.

This experiment shows that water is a poor conductor of heat. This is equally true of all liquids except molten metals.

364. Conductivity of Gases. — The conductivity of gases is very small, and its determination is very difficult because of radiation and convection. The conductivity of hydrogen is about 7.1 times that of air, while the conductivity of water is 25 times as great.

365. Applications of Conductivity. — If we touch a piece of marble or iron in a room, it feels cold, while cloth and wood feel distinctly warmer. The explanation is that the articles which feel cold are good conductors of heat and carry it away from the hand, while the poor conductors do not.

The good heat-conducting property of copper or brass is turned to practical account in Sir Humphry Davy's miner's lamp (Fig. 320).

The flame is completely inclosed in metal and fine wire gauze. The gauze by conducting away heat keeps any fire damp outside the lamp below the temperature of ignition and so prevents explosions. The action of the gauze is readily illustrated by holding it over the flame of a Bunsen burner (Fig. 321). The flame does not pass through unless the gauze is heated to redness. If the gas is first allowed to stream through the gauze, it may be lighted on top without being ignited below.

FIGURE 320. DAVY SAFETY LAMP.

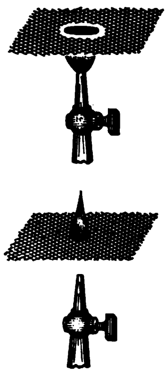


FIGURE 321.— FLAME STOPPED BY WIRE GAUZE.

The handles on metal instruments that are to be heated are usually made of some poor conductor, as wood, bone, etc.; or else they are insulated by the insertion of some non-conductor, as in the case of the handles to silver teapots, where pieces of ivory are inserted to keep them from becoming too hot.

The non-conducting character of air is utilized in houses with hollow walls, in double doors and double windows, and in clothing of loose texture. The warmth of woolen articles and of fur is due mainly to the fact that much air is inclosed within them on account of their loose structure.

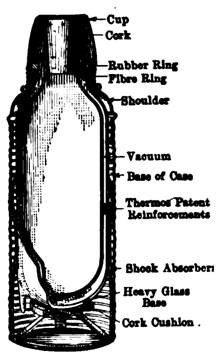


FIGURE 322.—THERMOS BOTTLE.

The *thermos bottle* consists of a glass bottle with double walls (Fig. 322). The space between the two walls is exhausted of air, and the inner walls of this vacuum are silvered to lessen radiation from one to the other. Either hot or cold liquids may be kept in a thermos bottle with little change of temperature for several hours.

The "*fireless cooker*" is a box of wood or steel with a metallic vessel inside. The two are separated by heavy felt or other poorly conducting material (Fig. 323). After the material to be cooked has been raised to the proper temperature, it is placed in the cooker and the latter is tightly closed. The high tem-

perature is maintained for three hours with a drop of not more than 10° or 15° C. The cooking may be completed without further application of heat. The conductivity of the lining and of the inclosed air is so low that heat escapes very slowly. Additional heat is often supplied by means of hot soapstone or cast iron disks.

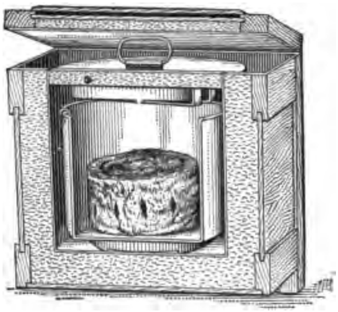


FIGURE 323. — FIRELESS COOKER.

366. Convection. — Set up apparatus as shown in Fig. 324, and support it on a heavy iron stand. Fill the flask and connecting tubes with water up to a point a little above the open end of the vertical tube at *C*. Apply a Bunsen flame to the flask *B*. A circulation of water is set up in the apparatus, as shown by the arrows. The circulation is made visible by coloring the water in the reservoir blue and that in the flask red.

The process of conveying heat by the transference of the heated matter itself is known as *convection*. Currents set up in this manner are called *convection currents*.

367. Heating by Hot Water. — The heating of buildings by hot water conveyed by pipes to the radiators and thence back again to the heater in the basement is an application of convection by liquids (Fig. 325). The hot water pipe extends to an open tank at the top of the building to allow for expansion. The circulation is maintained because the hot water in the pipes leading to the radiators is hotter and therefore lighter than the cooler water in the return pipes beyond the radiators.

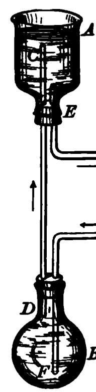


FIGURE 324. — CONVECTION CURRENTS.

368. The Hot Water Heater. — The simplest arrangement for heating water for general

domestic purposes is shown in Fig. 326. The cold water enters the tank at the top through a pipe which reaches nearly to the bottom. The pipe in the bottom leads to a heating coil in the gas heater. The hot water rises and enters the tank at or near the top, while heavier cold water takes its place in the heating coils. The circulation thus set up continues as long as heat is applied.

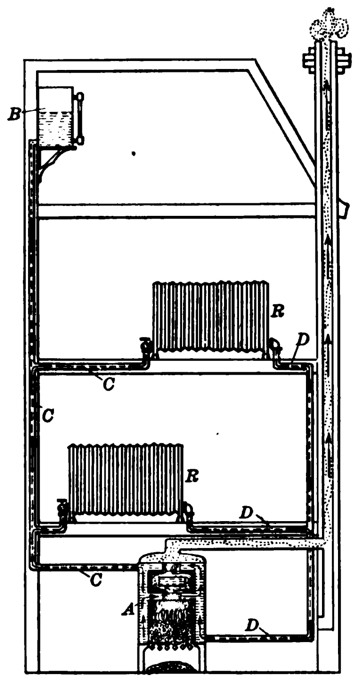


FIGURE 325.—HEATING BY HOT WATER.

369. Convection in Gases. — Set a short piece of lighted candle in a shallow beaker and place over it a lamp chimney. Pour into the beaker enough water to close the lower end of the chimney. Place in the top of the chimney a T-shaped piece of tin as a short partition (Fig. 327). If a piece of smoldering paper be held over one edge of the chimney, the smoke will pass down one side of the partition and up the other. If the partition be removed, the flame will usually go out.

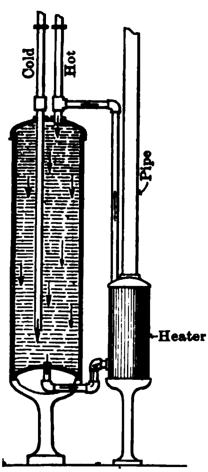


FIGURE 326. — WATER HEATER.

Convection currents are more easily set up in gases than in liquids. Convection currents of air on a large scale are present near the seacoast. The wind is

a sea breeze during the day, because the air moves in from the cooler ocean to take the place of the air rising over the heated land. As soon as the sun sets, the ground cools rapidly by radiation, and the air over it is cooler than over the sea. Hence the reversal in the direction of the wind, which is now a land breeze.

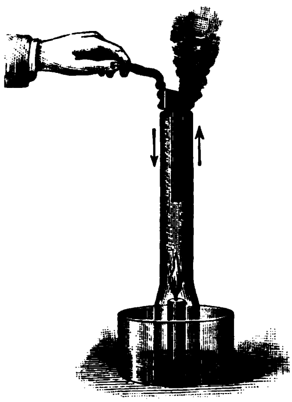


FIGURE 327. — CONVECTION IN GASES.

370. Heating and Ventilating by Hot Air. — The hot air furnace in the basement is a heater for burning wood, coal, distillate, or gas, and surrounded by a jacket of galvanized iron (Fig. 328). Cold air from outside is heated between the heater and the jacket and rises through the hot air flues to registers in the rooms of the building. In houses the extra air often finds an outlet through crevices and up open chimneys. A better way is to provide ventilation by means of separate flues. Since the heated air rises to the top of the room, it follows that if provision is made for the escape of the colder air by flues at the floor, the incoming air will force out the foul air, thus

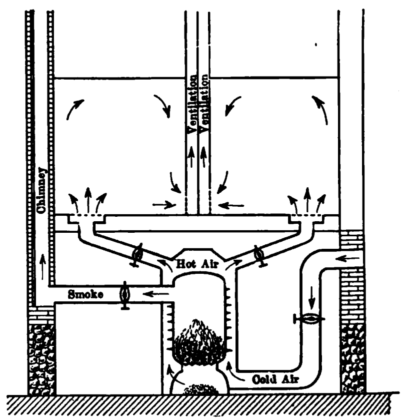


FIGURE 328. — HEATING BY HOT AIR.

changing the air of the room and warming it at the same time.

Large public buildings must have positive means of supplying fresh air to the extent of about 50 cubic feet per minute for each person. For this purpose large fans driven by power draw in fresh air from the outside and force it through flues throughout the building. The air is often washed or filtered on its way in, and in cold weather is heated by steam pipes. The foul air is forced out through openings near the floor. Sometimes exhaust fans draw out the vitiated air through the ventilating ducts.

371. Radiation. — When one stands near a hot stove, one is warmed neither by heat conducted nor conveyed by the air. The heat energy of a hot body is constantly passing into space as *radiant energy* in the ether (§ 243). Radiant energy becomes heat again only when it is absorbed by bodies upon which it falls. Energy transmitted in this way is, for convenience, referred to as *radiant heat*, although it is transmitted as radiant energy, and is transformed into heat only by absorption. Radiant heat and light are physically identical, but are perceived through different avenues of sensation. Radiations that produce sight when received through the eye give a sensation of warmth through the nerves of touch, or heat a thermometer when incident upon it. The long ether waves do not affect the eye, but they heat a body which absorbs them.

372. The Radiometer. — Long heat waves may be detected by the *radiometer*, an instrument invented by Sir William Crookes in 1873 while investigating the properties of highly attenuated gases. It consists of a glass bulb from which the air has been exhausted until the pressure

does not exceed 7 mm. of mercury (Fig. 329). Within the bulb is a light cross of aluminum wire carrying small vanes of mica, one face of each coated with lampblack. The whole is mounted to rotate on a vertical pivot. When the instrument is placed in the sunlight or in the radiation from any heated body, the cross revolves with the blackened faces of the vanes moving away from the source of heat.

FIGURE 329.—THE RADIOMETER.

The infrequent collisions among the molecules in such a vacuum prevent the equalization of pressure throughout the bulb. The blackened sides of the vanes absorb more heat than the bright ones, and the gas molecules rebound from the warmer surfaces with a greater velocity than from the others, thus giving the vanes an impulse in the opposite direction. This impulse is the equivalent of a pressure, which causes the vanes to revolve.

373. Laws of Heat Radiation. — Place a radiometer about 50 cm. from a small lighted lamp and note the effect on the radiometer. Support a cardboard screen between the lamp and the radiometer; the rotation of the radiometer at once becomes slower.

Hence, *Radiation proceeds in straight lines.* This law is illustrated in the use of fire screens and sunshades.

Lay a meter stick on a table and place the radiometer at one end of it and the lamp at the other. Count the number of revolutions of the vanes in one minute. Move the radiometer to a distance of 50 cm.

from the lamp and count the number of revolutions again for a minute. It will be about four times as many as before.

Hence, *The amount of radiant energy received by a body from any small radiant area varies inversely as the square of the distance from it as a source.* Note that this law is the same as that relating to the intensity of illumination in light (§ 252).

Support a plane mirror vertically on a table. *At right angles to it* and distant about 5 cm. support a vertical cardboard screen about 50 cm. long and 20 cm. wide. On one side of this screen place a lighted lamp and on the other the radiometer. The vanes will revolve rapidly whenever the lamp and the radiometer are in such a position that the screen bisects the angle made by lines drawn from them to the same point on the mirror. The angles between these lines and the screen are the angles of incidence and reflection of the radiant energy.

Hence, *Radiant energy is reflected from a polished surface so that the angles of incidence and reflection are equal.*

Select two concave wall lamp reflectors of the same size and blacken one of them in the smoke from burning camphor gum. Place a lighted lamp about one meter from the radiometer and observe the rate of rotation of the vanes. Hold the clear reflector back of the radiometer, so as to concentrate the radiation from the lamp upon it, and again note the rate of rotation. Now substitute the blackened reflector for the clear one; the rate of rotation will be greatly reduced.

Hence, *The capacity of a surface to reflect radiant energy depends both on the polish of the surface and on the nature of the material.* Polished brass is one of the best reflectors and lampblack is the poorest.

374. Heat Transparency. — Select two flat twelve ounce bottles; fill one with water and the other with a solution of iodine in carbon disulphide. Cut an opening in a sheet of black cardboard of such a

size that either bottle will cover it. Place this cardboard between the lamp and the radiometer and note the effect on the radiometer as the opening is closed successively by the bottles. This experiment and others similar to it show that

The transmission of radiant energy through various substances depends on the temperature of the source, and the thickness and nature of the substance itself.

Substances that transmit a large part of the heat energy, such as the solution of iodine and rock salt, are said to be *diathermanous;* those absorbing a large part, such as water, are *athermanous.* Glass is diathermanous to radiations from a source of high temperature, such as the sun, but athermanous to radiations from sources of low temperature, such as a stove. The radiant energy from the sun passes readily through the atmosphere to the earth, and warms its surface; but the radiations from the earth are stopped to a large extent by the surrounding atmosphere. This selective absorption is due in large measure to the vapor of water in the air.

Questions

1. Why will newspapers spread over plants protect them from frost?

2. Why does a tall chimney have a stronger draft than a short one?

3. Explain how it is possible to boil water in a paper pail without burning the pail.

4. Should the surface of a steam or hot water radiator be rough or polished?

5. In what way does a stove heat a room?

6. Why does a woolen garment feel warmer than a cotton or a linen one?

7. Why is glass an effective screen?

8. Why does steam burn more severely than hot water?

9. Why should the registers for removing impure air be placed at the floor level?

10. What principles of heat are applied in the radiator of an automobile?

11. Why will the moistened finger or the tongue freeze quickly to a piece of very cold iron, but not to a piece of wood?

12. Why is the boiling point of water in the boiler of a steam engine above 100° C.?

VII. HEAT AND WORK

375. Heat from Mechanical Action. — Strike the edge of a piece of flint a glancing blow with a piece of hardened steel. Sparks will fly at each blow.

Pound a bar of lead vigorously with a hammer. The temperature of the bar will rise.

In the cavity at the end of a piston of a fire syringe place a small piece of tinder, such as is employed in cigar lighters (Fig. 330). Force the piston quickly into the barrel. If the piston is immediately withdrawn the tinder will probably be on fire.

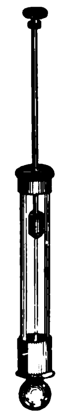


FIGURE 330. — FIRE SYRINGE.

These experiments show that mechanical energy may be transformed into heat. Some of the energy of the descending flint, the hammer, and the piston has in each case been transferred to the molecules of the bodies themselves, increasing their kinetic energy, that is, raising their temperature.

Savages kindle fire by rapidly twirling a dry stick, one end of which rests in a notch cut in a second dry piece. The axles of carriages and the bearings in machinery are heated to a high temperature when not properly lubricated. The heating of drills and bits in boring, the heating of saws in cutting timber, the burning

of the hands by a rope slipping rapidly through them, the stream of sparks flying from an emery wheel, are instances of the same kind of transformation; the work done against friction produces kinetic energy in the form of heat.

376. The Mechanical Equivalent of Heat. — In 1840 Joule of Manchester in England began a series of experiments to determine the numerical relation between the unit of heat and the foot pound. His experiments extended over a period of forty years. His most successful method consisted in measuring the heat produced when a measured amount of work was expended in heating water by stirring it with paddles driven by weights falling through a known height. His final result was that 772 ft.-lb. of work, when converted into heat, raise the temperature of 1 lb. of water 1° F., or 1390 ft.-lb. for 1° C. The later and more elaborate researches of Rowland in 1879 and of Griffiths in 1893 show that the relation is 778 ft.-lb. for 1° F., or 427.5 kg.-m. for 1° C.; that is, if the work done in lifting 427.5 kg. one meter high is all converted into heat, it will raise the temperature of 1 kg. of water 1° C. This relation is known as *the mechanical equivalent of heat.* Its value expressed in absolute units is 4.19×10^7 ergs per calorie.

377. The Steam Engine. — The most important devices for the conversion of heat into mechanical work are the steam engine and the gas engine. The former in its essential features was invented by James Watt. In the reciprocating steam engine a piston is moved alternately in opposite directions by the pressure of steam applied first to one of its faces and then to the other. This reciprocating or to-and-fro motion is converted into rotatory motion by the device of a connecting rod, a crank, and a flywheel.

James Watt (1736–1819) was born at Greenock, Scotland, and was educated as an instrument maker. In studying the defects of the steam engines then in use, he was led to make many very important improvements, culminating in his invention of the double-acting steam engine. He invented the ball governor, the cylinder jacket, the D-valve, the jointed parallelogram for securing rectilinear motion to the piston, the mercury steam-gauge, and the water-gauge. He is also to be credited with the first compound engine, a type of engine extensively used to-day.

James Prescott Joule (1818–1889), the son of a Manchester brewer, was born at Salford, England. He became known to the scientific world through his contributions in heat, electricity, and magnetism. His greatest achievement was establishing the modern kinetic theory of heat by determining the mechanical equivalent of heat. His experiments on this subject were continued through a period of forty years. In recognition of his great work he was presented with the Royal Medal of the Royal Society of England in 1852.

In Fig. 331 are shown in section the cylinder, piston, and valve of a *slide-valve steam engine.* The piston *B* is moved in the cylinder *A* by the pressure of the steam admitted through the inlet pipe *a.* The slide valve *d* works in the steam chest *cc* and admits steam alternately to the two ends of the cylinder through the steam ports at either end.

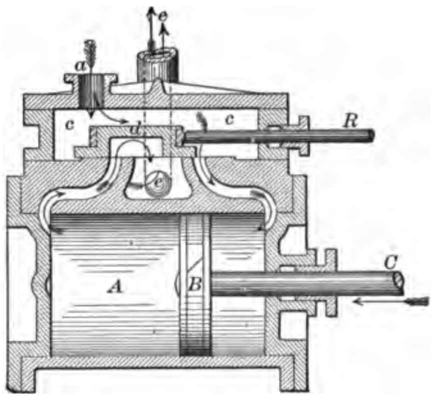


FIGURE 331. — CYLINDER OF STEAM ENGINE.

When the valve is in the position shown, steam passes into the right-hand end of the cylinder and drives the piston toward the left. At the same time the other end is connected with the exhaust pipe *ee* through which the steam escapes, either into the air, as in a *high-pressure non-condensing engine*, or into a large condensing chamber, as in a *low pressure condensing engine.*

The slide valve *d* is moved by the rod *R*, connected to an eccentric, which is a round disk mounted a little to one side of its center, on the engine shaft. It has the effect of a crank. The flywheel, also mounted on the shaft of the engine, has a heavy rim and serves as a store of energy to carry the shaft over the dead points when the piston is at either end of the cylinder. There is in the flywheel a give-and-take of energy twice every revolution, and a fairly steady rotation of the shaft is the result.

The eccentric is set in such a way that the rod *R* closes the valve admitting steam to either end of the cylinder

before the piston has completed its stroke; the motion of the piston is continued during the remainder of the stroke by the expansive force of the steam.

Corliss valves are commonly used in large slow speed engines. As distinguished from the slide valve, the Corliss valve is cylindrical and opens and closes by turning a little in its seat, first in one direction and then the other. In the Corliss engine there are four such valves, two at each end of the steam cylinder. One of each pair admits steam to the cylinder and the other is the exhaust valve. When the inlet valve is open at one end of the steam cylinder, the exhaust valve is open at the other end. All four valves are opened and closed automatically by the motion of the engine itself. Each valve can be adjusted separately.

378. The Indicator Diagram. — The steam indicator is a device for the automatic tracing of a diagram representing the relation between the volume and the pressure of the steam in the cylinder during one stroke. This diagram is known as an "indicator card" (Fig. 332).

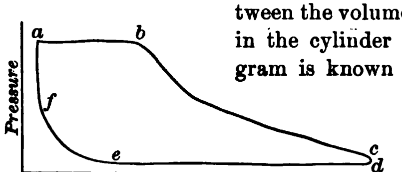
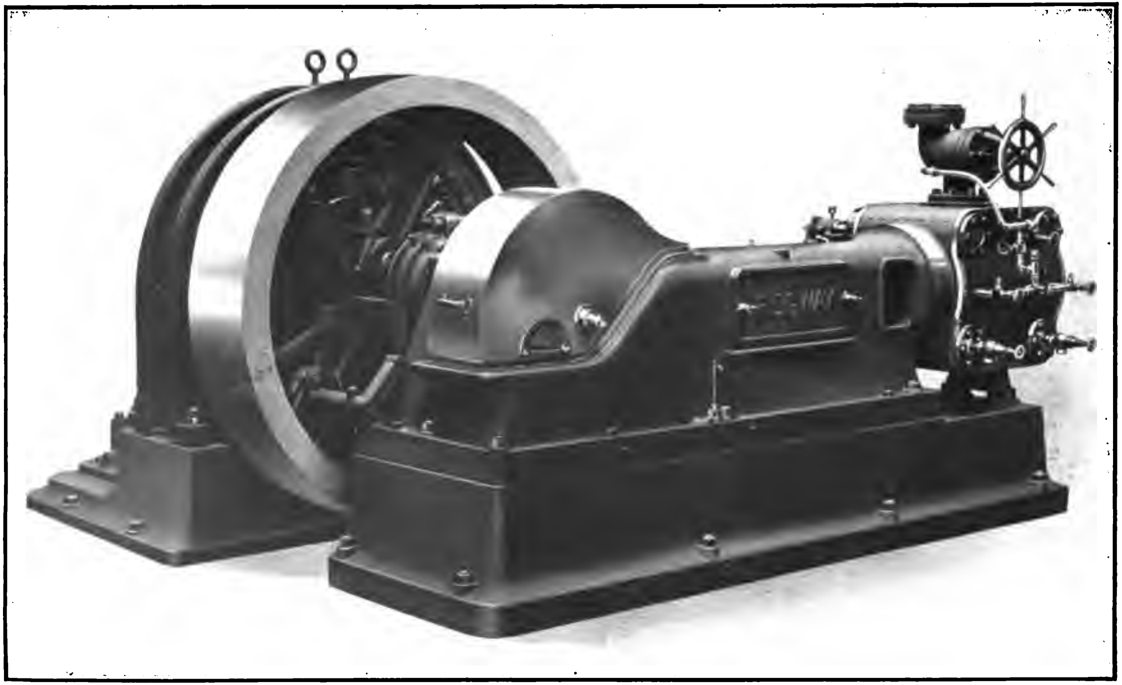


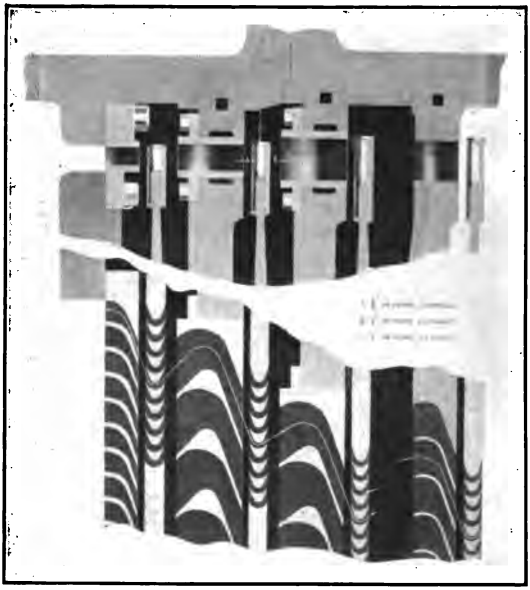
FIGURE 332. — INDICATOR DIAGRAM.

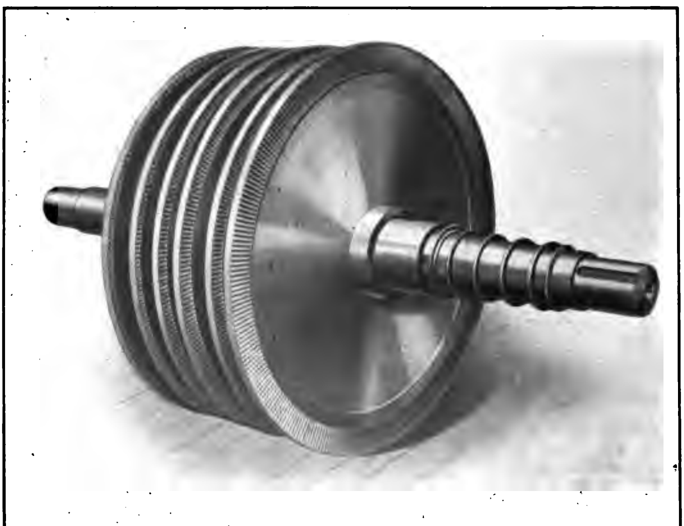
From a to b the inlet port is open and the full pressure of steam is on the piston; at b the inlet port closes and the steam expands from b to c, when the exhaust port opens; at d the pressure is reduced to the lowest value and remains sensibly constant during the return movement of the piston until e is reached, when the exhaust port closes and the remaining steam is compressed from e to f. At f the inlet port opens and the pressure rises abruptly to the initial maximum, thus completing the cycle. The work done during the stroke is represented by the inclosed area *abcdef*. The indicator card is used also in adjusting the valves.

379. The Steam Turbine. — The steam turbine has the great advantage of producing rotary motion directly with-



A 4-Valve Engine Directly Connected to a Dynamo-electric Machine.





ABOVE: SECTION THROUGH THE STEAM TURBINE, SHOWING NOZZLES AND BUCKETS.
BELOW: THE ROTOR OF A TURBINE, SHOWING BUCKETS INCREASING IN SIZE FROM LEFT TO RIGHT.

out the intervention of a connecting rod and crank to convert the back and forth motion of the piston in a reciprocating engine into rotary motion. In the latter the piston stops and starts again twice during each revolution of the flywheel, and the stopping and starting gives rise to disagreeable vibrations. In the steam turbine the rotor revolves continuously and the impulses it receives are constant instead of intermittent.

Steam enters the turbine through a set of stationary nozzles, shown in section in the half tone. Here it expands and acquires a high velocity. It then strikes the entrance edge of the first row of buckets in the rotor, gives up energy to them, and drives them forward as it passes through. It then passes through the second set of stationary nozzles, of greater area than the first; here it again expands, increases its velocity, and enters the second row of buckets. The process is repeated in successive stages until it reaches the exhaust outlet. By its impulse on each row of buckets it gives up energy to the rotor. The half tone of a complete rotor shows the increasing size of the buckets from left to right. The buckets are curved openings through the rotor, as shown in section in the half tone.

380. The Gas Engine. — The *gas engine* is a type of *internal combustion engine*, which includes motors using gas, gasoline, kerosene, or alcohol as fuel. The fuel is introduced into the cylinder of the engine, either as a gas or as a vapor, mixed with the proper quantity of air to produce a good explosive mixture. The mixture is ignited at the right instant by means of an electric spark. The explosion and the expansive force of the hot gases drive the piston forward in the cylinder.

In the *four-cycle* type of gas engine, the explosive mix-

ture is drawn in and ignited in each cylinder only every other revolution of the engine, while in the *two-cycle* type an explosion occurs every revolution. The former type is used in most motor car engines, and the latter in small motor boats.

The operation of a four-cycle engine is illustrated in 1, 2, 3, and 4 of Fig. 333, which shows the four steps in a complete cycle. The inlet valve *a* and the exhaust valve *b* are operated by the cams *c* and *d*. Both valves are kept normally closed by springs surrounding the valve stems. The small shafts to which the two cams are fixed are driven by the spur wheel *e* on the shaft of the engine. This wheel engages with the two larger spur wheels on the cam shafts, each having twice as many teeth as *e* and forming with it a two-to-one gear, so that *c* and *d* rotate once in every two revolutions of the crank shaft. The piston *m* has packing rings; *h* is the connecting rod, *k* the crank shaft, and *l* the spark plug.

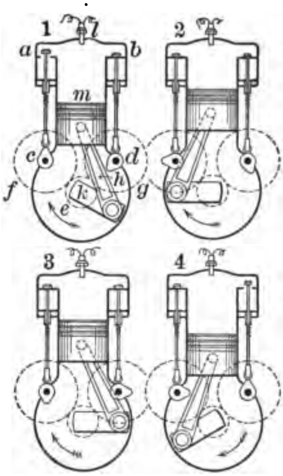


FIGURE 333.—SHOWING FOUR STEPS IN CYCLE.

In diagram 1 the piston is descending and draws in the charge through the open valve *a*; in 2 both valves are closed and the piston compresses the explosive charge; about the time the piston reaches its highest point, the charge is ignited by a spark at the spark plug, and the working stroke then takes place, as in 3, both valves remaining closed; in 4 the exhaust valve *b* is opened by the cam *d*, and the products of the combustion escape

through the muffler, or directly into the open air. The piston has now traversed the cylinder *four times*, twice in in each direction, and the series of operations begins again.

381. Two-Cycle Engine. — Figure 334 is a section of a two-cycle gas engine. During the up-stroke of the piston *P* a charge is drawn through *A* into the crank case *C*. At the same time a charge in the cylinder is compressed and is ignited by a spark when the compression is greatest. The piston is forced down, and when it passes the port *E* the exhaust takes place. When the admit port *I* is passed, a charge enters from the crank case. To prevent this charge from passing across and escaping at *E*, it is made to strike against a projection *B* on the piston, which deflects it upward. The momentum of the balance wheel carries the piston upward, compresses the charge, and draws a fresh charge into the crank case. The piston has now traversed the cylinder *twice*, once in each direction, and the same series of operations is again repeated.

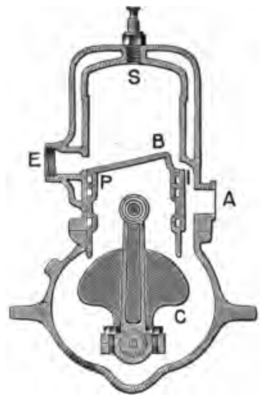


FIGURE 334. — SECTION OF TWO-CYCLE ENGINE.

382. The Aëroplane. — The principle of the aëroplane has already been described in § 124. It is a "heavier than air" machine and is lifted as the kite is lifted ; but instead of the wind blowing against it, it is forced against the air by a powerful gas engine, driving a high speed propeller. Formerly the engine and the propeller were placed at the rear end, as in a steamship, but recent practice is to mount one or two engines and propellers in front. Such machines are known as traction aëroplanes.

Questions and Problems

1. Why does the temperature of the air under the bell jar of an air pump fall when the pump is worked?

2. Is there a difference in the temperature of the steam as it enters a steam engine and as it leaves at the exhaust? Explain.

3. Lead bullets are sometimes melted when they strike a target. Explain.

4. Does clothing keep the cold out or keep the heat in?

5. Is there any less moisture in the air after it has passed through a heated furnace into a room than there was before?

6. Why does the rapid driving of an automobile heat the air in the tires?

7. A mass of 200 g. moving with a speed of 50 m. per second is suddenly stopped. If all its energy is converted into heat, how many calories would be generated?

NOTE. A calorie equals 4.19×10^7 ergs.

8. If all the potential energy of a 300 kg. mass of rock is converted into heat by falling vertically 200 m., how many calories would be generated?

9. How high could a 200 g. weight be lifted by the heat required to melt the same mass of ice, if all the heat could be utilized for the purpose?

10. If the average pressure of steam in the cylinder of an engine is 100 lb. per square inch, the area of the piston is 80 sq. in., and the stroke 1 ft., how many horse powers would be developed if the engine makes two revolutions per second?

CHAPTER X

MAGNETISM

I. MAGNETS AND MAGNETIC ACTION

383. Natural Magnets or Lodestones. — Black oxide of iron, known to mineralogists as *magnetite*, is found in many parts of the world, notably in Arkansas, the Isle of Elba, Spain, and Sweden. Some of these hard black stones are found to possess the property of attracting to them small pieces of iron. At a very early date such pieces of iron ore were found near Magnesia in Asia Minor, and they were therefore called *magnetic stones* and later *magnets*. They are now known as *natural magnets*, and the properties peculiar to them as *magnetic properties*.

Dip a piece of natural magnet into iron filings; they will adhere to it in tufts, not uniformly over its surface, but chiefly at the ends and on projecting edges (Fig. 335).

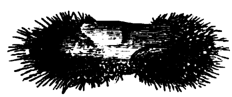


FIGURE 335. — NATURAL MAGNET.

Suspend a piece of natural magnet by a piece of untwisted thread (Fig. 336), or float it on a wooden raft on water. Note its position, then disturb it slightly, and again let it come to rest. It will be found that it invariably returns to the same position, the line connecting the two ends to which the filings chiefly adhered in the preceding experiment lying north and south.

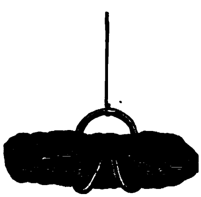


FIGURE 336. — NATURAL MAGNET SUSPENDED.

This directional property of the natural magnet was early turned to account

in navigation, and secured for it the name of *lodestone* (leading-stone).

384. Artificial Magnets. — Stroke the blade of a pocket knife from end to end, and always in the same direction, with one end of a lodestone. Touch it to iron filings; they will cling to its point as they did to the lodestone. The knife blade has become a magnet.

Use the knife blade of the last experiment to stroke another blade. This second blade will also acquire magnetic properties, and the first one has suffered no loss.

Artificial magnets, or simply magnets, are bars of hardened steel that have been made magnetic by the application of some other magnet or magnetizing force. The form of artificial magnets most commonly met with are the *bar* and the *horseshoe*.

385. Magnetic Substances. — Any substance that is attracted by a magnet or that can be magnetized is a *magnetic substance.* Faraday showed that most substances are influenced by magnetism, but not all in the same way nor to the same degree. Iron, nickel, and cobalt are strongly attracted by magnets and are said to be *magnetic;* bismuth, antimony, phosphorus, and copper act as if they are repelled by magnets and they are called *diamagnetic.* Most of the alloys of iron are magnetic, but manganese steel is non-magnetic.


FIGURE 337. — MAGNET TUFTED WITH IRON FILINGS.

386. Polarity. — Roll a bar magnet in iron filings. It will become thickly covered with the filings near its end. Few, if any, will adhere at the middle (Fig. 337).

The experiment shows that the greater part of the magnetic attraction is concentrated at or near the ends of the magnet. They are called its *poles*, and the magnet is said

to have *polarity*. The line joining the poles of a long slender magnet is its *magnetic axis*.

387. North and South Poles. — Straighten a piece of watch spring 8 or 10 cm. long, stroke it from end to end with a magnet, and float it on a cork in a vessel of water (Fig. 338). It will turn from any other position to a north and south one, and invariably with the same end north.

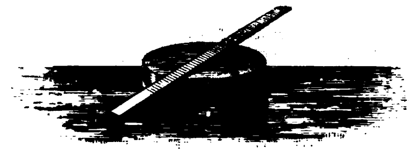


FIGURE 338. — FLOATING MAGNET.

The end of a magnet pointing toward the north is called the *north-seeking pole*, and the other, the *south-seeking pole*. They are commonly called simply the *north pole* and the *south pole*.

388. Magnetic Needle. — A slender magnetized bar, suspended by an untwisted fiber or pivoted on a point so as to have freedom of motion about a vertical axis is a *magnetic needle* (Fig. 339). The direction in which it comes to rest without torsion or friction is called the *magnetic meridian*.

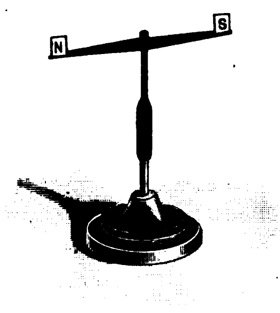


FIGURE 339. — MAGNETIC NEEDLE.

Fasten a fiber of unspun silk to a piece of magnetized watch spring about 2 cm. long so that it will hang horizontally. Suspend it inside a wide-mouthed bottle by attaching the fiber to a cork fitting the mouth of the bottle. The little magnetic needle will then be protected from currents of air. It may be made visible at a distance by sticking fast to it a piece of thin white paper.

389. Magnetic Transparency. — Cover the pole of a strong bar magnet with a thin plate of glass. Bring the face of the plate opposite the pole in contact with a pile of iron tacks. A number will be

found to adhere, showing that the attraction takes place through glass. In like manner, try thin plates of mica, wood, paper, zinc, copper, and iron. No perceptible difference will be seen except in the case of the iron, where the number of tacks lifted will be much less.

Magnetic force acts freely through all substances except those classified as *magnetic*. Soft iron serves as a more or less perfect screen to magnetism. Watches may be protected from magnetic force that is not too strong by means of an inside case of soft sheet iron.

390. First Law of Magnetic Action. — Magnetize a piece of large knitting needle, about four inches long, by stroking it from the middle to one end with the north pole of a bar magnet, and then from the middle to the other end with the south pole. Repeat the operation several times. Present the north pole of the magnetized knitting needle to the north pole of the needle suspended in the bottle. The latter will be repelled. Present the same pole to the south pole of the little magnetic needle; it will be attracted. Repeat with the south pole of the knitting needle and note the deflections.

The results may be expressed by the following law of magnetic attraction and repulsion :

Like magnetic poles repel and unlike magnetic poles attract each other.

391. Testing for Polarity. — The magnetic needle affords a ready means of ascertaining which pole of a magnet is the north pole, for the north pole of the magnet is the one that repels the north pole of the magnetic needle. ***Repulsion is the only sure test of polarity*** for reasons that will appear in the experiments that follow.

392. Induced Magnetism. — Hold vertically a strong bar magnet and bring up against its lower end a short cylinder of soft iron. It will adhere. To the lower end of this one attach another, and so on

in a series of as many as will stick (Fig. 340). Carefully detach the magnet from the first piece of iron and withdraw it slowly. The pieces of iron will all fall apart.

The small bars of iron hold together because they become temporary magnets. Magnetism produced in magnetic substances by the influence of a magnet near by or in contact with them is said to be *induced*, and the action is called *magnetic induction*. Magnetic induction precedes attraction.

FIGURE 340. — INDUCED MAGNETISM.

393. Unlike Polarity Induced. — Place a bar magnet in line with the magnetic axis of a magnetic needle, with its north pole as near as possible to the north pole of the needle without appreciably repelling it (Fig. 341). Insert a bar of soft iron between the magnet and the needle. The north pole of the needle will be immediately repelled.

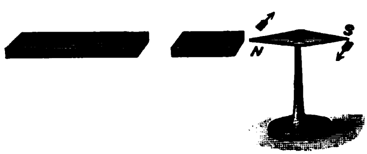


FIGURE 341. — POLARITY BY INDUCTION.

The repulsion of the north pole of the needle by the end of the soft iron bar next to it shows that this end of the bar has acquired a polarity the same as that of the magnet, that is, north polarity. Then the other end adjacent to the magnet must have acquired the opposite polarity.

When a magnet is brought near a piece of iron, the iron is magnetized by induction, and there is attraction because the adjacent poles are unlike. When a bunch of iron filings or tacks adhere to a magnet, each filing or tack becomes a magnet and acts inductively on the others and all become magnets. Weak magnets may have their polarity reversed by the inductive action of a strong magnet.

394. Permanent and Temporary Magnetism. — When a piece of hardened steel is brought near a magnet, it acquires magnetism as a piece of soft iron does under the same conditions: but the steel retains its magnetism when the magnetizing force is withdrawn, while the soft iron does not. In the experiment of § 392 the soft iron ceases to be a magnet when removed to a distance from the bar magnet. In addition, therefore, to the *permanent magnetism* exhibited by the magnetized steel, we have *temporary magnetism* induced in a bar of soft iron when it is brought near a magnet or in contact with it.

II. NATURE OF MAGNETISM

395. Magnetism a Molecular Phenomenon. — If a piece of watch spring be magnetized and then heated red hot, it will lose its magnetism completely.

A magnetized knitting needle will not pick up as many tacks after being vibrated against the edge of a table as it did before.

FIGURE 342. — BENT MAGNET.

A piece of moderately heavy and very soft iron wire of the form shown in Fig. 342 can be magnetized by stroking it gently with a bar magnet. If given a sudden twist, it loses at once all the magnetism imparted to it.

A piece of watch spring attracts iron filings only at its ends. If broken in two in the middle, each half will be a magnet and will attract filings, two new poles having been formed where the original magnet was neutral. If these pieces in turn be broken, their parts will be magnets. If this division into separate magnets be conceived to be carried as far as the molecules, they too would probably be magnets.

It is worthy of notice that magnetization is facilitated by jarring the steel, or by heating it and letting it cool under the influence of a magnetizing force. If an iron bar is rapidly magnetized and demagnetized, its temperature is raised. A steel rod is slightly lengthened by

magnetization and a faint click may be heard if the magnetization is sudden.

396. Theory of Magnetism. — The facts of the preceding section indicate that the seat of magnetism is the molecule, that the individual molecules are magnets, that in an unmagnetized piece of iron the poles of the molecular magnets are turned in various directions, so that they form stable combinations or closed magnetic chains, and hence exhibit no magnetism external to the bar (Fig. 343). In a magnetized bar the larger portion of the molecules have their magnetic axes pointing in the same direction (Fig. 344), the completeness of the magnetization depending on the completeness of this alignment.

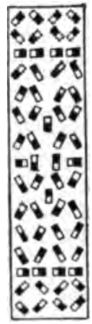


FIGURE 343. — UNMAGNETIZED BAR.

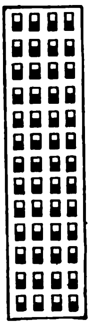


FIGURE 344. — MAGNETIZED BAR.

III. THE MAGNETIC FIELD

397. Lines of Magnetic Force. — Place a sheet of paper over a small bar magnet and sift iron filings evenly over it from a bottle with a piece of gauze tied over the mouth, tapping the paper gently to aid the filings in arranging themselves under the influence of the magnet. They will cling together in curved lines, which diverge from one pole of the magnet and meet again at the opposite pole.

These lines are called *lines of magnetic force* or of *magnetic induction.* Each particle of iron becomes a magnet by induction; hence *the lines of force are the lines along which magnetic induction takes place.*

398. Magnetic Fields. — *A magnetic field is the space around a magnet in which there are lines of magnetic force.*

Figure 345 was made from a photograph of the magnetic field of a bar magnet in a plane passing through the magnetic axis. These lines branch out nearly radially from one pole and curve round through the air to the other pole. Faraday gave to them the name

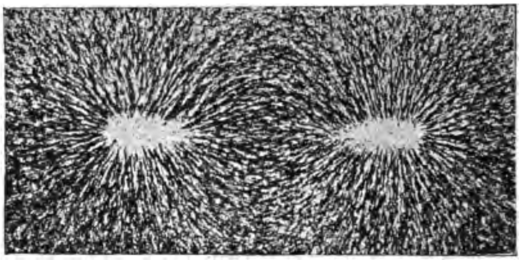


FIGURE 345. — MAGNETIC FIELD OF BAR MAGNET.

lines of force. The curves made by the iron filings "represent visibly the invisible lines of magnetic force."

Figure 346 shows the field about two bar magnets placed with their unlike poles adjacent to each other. Many of the lines from the north pole of the one extend across to the south pole of the other, and this connection denotes attraction.

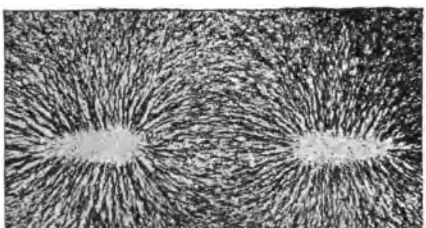


FIGURE 346. — MAGNETIC FIELD, TWO UNLIKE POLES.

Figure 347 shows the field about two bar magnets with their like poles adjacent to each other. None of the lines springing from either pole extend across to the neighboring pole of the other magnet. This is a picture of magnetic repulsion.

399. Properties of Lines of Force. — Lines of magnetic force have the following properties: (*a*) They are under tension, exerting a pull in the direction of their length;

(*b*) they spread out as if repelled from one another at right angles to their length; (*c*) they never cross one another.

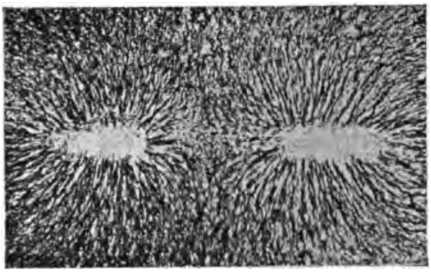


FIGURE 347. — MAGNETIC FIELD, TWO LIKE POLES.

400. Direction of Lines of Force. — Hold a mounted magnetic needle about 1 cm. long near a bar magnet. It will place itself tangent to the line of force passing through it.

Suspend by a fine thread about 60 cm. long a strongly magnetized sewing needle with its north pole downward. Bring this pole of the needle over the north pole of a horizontal bar magnet (Fig. 348). It will be repelled and will move along a curved line of force toward the south pole of the magnet.

The direction of a line of force at any point is that of a line drawn tangent to the curve at that point, and the positive direction is that in which a north pole is urged. Since the north pole of a magnetic needle is repelled by the north pole of a bar magnet, an observer standing with his back to the north pole of a magnet looks in the direction of the lines of force coming from that pole.

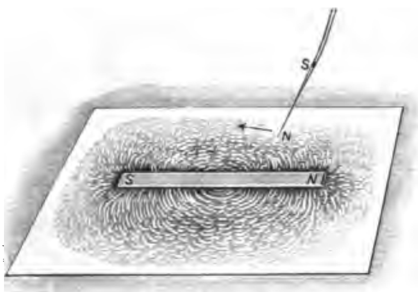


FIGURE 348. — DIRECTION OF LINES OF FORCE.

401. Permeability. — Place a piece of soft iron near the pole of a bar magnet and map out the field with iron filings. The lines are displaced by the iron and are gathered into it (Fig. 349).

When iron is placed in a magnetic field, the lines of force are concentrated by it. This property possessed by iron, when placed in a magnetic field, of concentrating the lines of force and increasing their number, is known as *permeability*. The superior permeability of soft iron explains the action of magnetic screens (§ 389). In the case of the watch shield, the lines of force follow the iron and do not cross it; the watch is thus protected from magnetism because the lines of force do not pass through it except when the magnetic field is very strong.

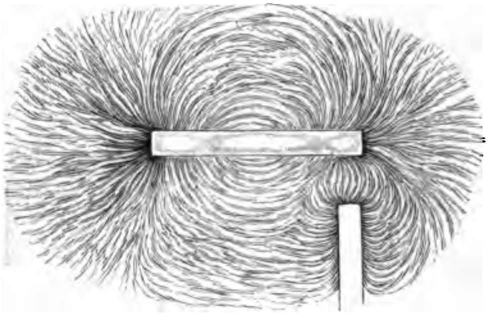


FIGURE 349. — DISPLACEMENT OF LINES.

IV. TERRESTRIAL MAGNETISM

402. The Earth a Magnet. — Support a thoroughly annealed iron rod or pipe horizontally in an east-and-west line and test it for polarity. It should show no magnetism. Now place it north and south with the north end about 70° below the horizontal (Fig. 350). While in this position, tap it with a hammer and then test it for polarity. The lower end will be found to be a north pole and the upper end a south pole. Turn the rod end for end, hold in the former position, and tap again with a hammer. The lower end will again become a north pole; the magnetism has been reversed.

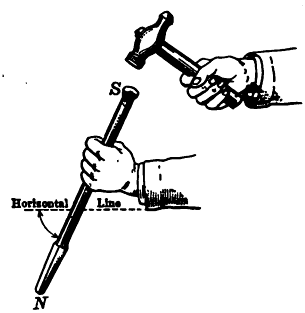


FIGURE 350. — EARTH INDUCED MAGNETISM.

This experiment shows that the earth acts as a magnet on the iron rod and magnetizes it by induction. Similarly, iron objects, such as a stove, a radiator, vertical steam pipes, iron columns, and hitching posts, become magnets with the lower end a north pole. The inductive action of the earth as a magnet accounts for the magnetism of natural magnets.

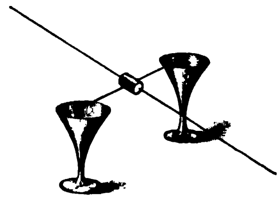


FIGURE 351. — MAGNETIC DIP.

403. Magnetic Dip. — Thrust two unmagnetized knitting needles through a cork at right angles to each other (Fig. 351). Support the apparatus on the edges of two glasses, with the axis in an east-and-west line, and the needle adjusted so as to rest horizontally. Now magnetize the needle, being careful not to displace the cork. It will no longer assume a horizontal position, the north pole dipping down as if it had become heavier.

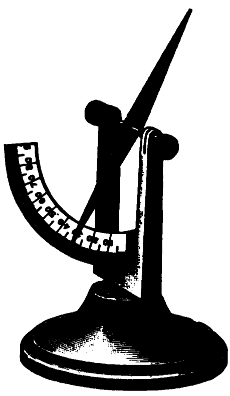


FIGURE 352. — DIPPING NEEDLE.

The *inclination* or *dip* of a needle is the angle its magnetic axis makes with a horizontal plane. A needle mounted so as to turn about a horizontal axis through its center of gravity is a *dipping needle* (Fig. 352). The dip of the needle at the magnetic poles of the earth is 90°, at the magnetic equator, 0°. In 1907 Amundsen placed the magnetic pole of the northern hemisphere in latitude 75° 5′ N. and longitude 96° 47′ W. The magnetic pole of the southern hemisphere is probably near latitude 72° S. and longitude 155° E.

Isoclinic lines are lines on the earth's surface passing through points of equal dip. They are irregular in di-

rection, though resembling somewhat parallels of latitude.

404. Magnetic Declination. — The magnetic poles of the earth do not coincide with the geographical poles, and consequently the direction of the magnetic needle is not in general that of the geographical meridian. The angle between the direction of the needle and the meridian at any place is the *magnetic declination.* To Columbus belongs the undisputed discovery that the declination is different at different points on the earth's surface. In 1492 he discovered a place of no declination in the Atlantic Ocean north of the Azores. The declination at any place is not constant, but changes as if the magnetic poles oscillate, while the mean position about which they oscillate is subject to a slow change of long period. The annual change on the Pacific coast is about 4′, and in New England about 3′. At London in 1657 the magnetic declination was zero, and it attained its maximum westerly value of 24° in 1816; in 1915 it was 15° 19′ W.

405. Agonic Lines. — Lines drawn through places where the needle points true north are called *agonic lines.* In 1910 the agonic line in North America ran from the magnetic pole southward across Lake Superior, thence near Lansing, Michigan, Columbus, Ohio, through West Virginia and South Carolina, and it left the mainland near Charleston on its way to the magnetic pole in the southern hemisphere. East of this line the needle points west of north; west of it, it points east of north. Lines passing through places of the same declination are called *isogonic lines.*

Questions

1. Given a bar magnet of unmarked polarity; determine which end is its north pole.

2. Out of a group of materials, how would you select the magnetic substances?

3. Given two bars exactly alike in appearance, one soft iron and the other hardened steel. Select the steel one by means of magnetism.

4. Magnetize a long darning needle, then break it in the middle. Will there be two magnets, each with one pole?

5. How would you magnetize a sewing needle so that the eye is the north pole?

6. What effect would it have on a compass to place it within an iron kettle?

7. Will an iron fence post standing in the ground have any influence on the needle of a surveyor's compass?

8. Float a magnet on a cork. Will the earth's magnetism cause it to float toward the earth's magnetic pole?

9. Is the polarity of the earth's magnetism in the northern hemisphere the same as that of the north pole of a magnet?

10. Suppose you wish to make a magnetic needle. If it is balanced on a point so as to rest in a horizontal position before magnetization, will it rest horizontally after it is magnetized?

CHAPTER XI

ELECTROSTATICS

I. ELECTRIFICATION

406. Electrical Attraction. — Rub a dry flint glass rod with a silk pad and bring it near a pile of pith balls, bits of paper, or chaff. They will at first be attracted and then repelled (Fig. 353).

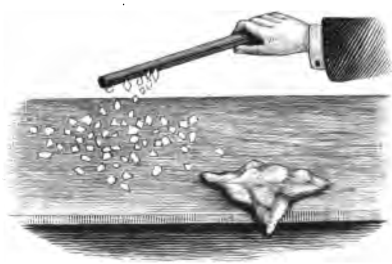


FIGURE 353. — ELECTRICAL ATTRACTION.

The simple fact that a piece of amber (a fossil gum) rubbed with a flannel cloth acquires the property of attracting bits of paper, pith, or other light bodies, has been known since about 600 B.C.; but it seems not to have been known down to the time of Queen Elizabeth that any bodies except amber and jet were capable of this kind of excitation. About 1600 Dr. Gilbert discovered that a large number of substances, such as glass, sulphur, sealing wax, resin, etc., possess the same peculiar property. These he called *electrics* (from the Greek word for amber, *electron*). A body excited in this manner is said to be *electrified*, its condition is one of *electrification*, and the invisible agent to which the phenomenon is referred is *electricity*.

407. Electrical Repulsion. — Suspend several pith balls from a glass hook (Fig. 354). Touch them with an electrified glass tube. They are at first attracted but they soon fly away from the tube and from one another. When the tube is removed to a distance, the balls no longer hang side by side, but keep apart for some little time. If we bring the hand near the balls they will move toward it as if attracted, showing that the balls are electrified.

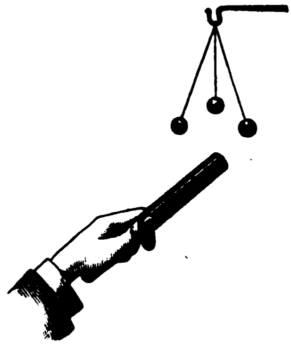


FIGURE 354. — ELECTRICAL REPULSION.

From this experiment it appears that bodies become electrified by coming in contact with electrified bodies, and that electrification may show itself by repulsion as well as by attraction.

408. Attraction Mutual. — Electrify a flint glass tube by friction with silk, and hold it near the end of a long wooden rod resting in a wire stirrup suspended by a silk thread (Fig. 355). The suspended rod is attracted. Now, replace the rod by the electrified tube. When the rod is held near the rubbed end of the glass tube, the latter moves as if attracted by the former.

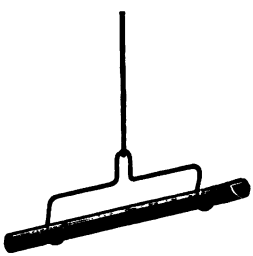


FIGURE 355. — ATTRACTION MUTUAL.

The experiment teaches that each body attracts the other; that is, *the action is mutual.*

409. Two Kinds of Electrification. — Rub a glass tube with silk and suspend it as in Fig. 355. Rub a second glass tube and hold it near one end of the suspended one. The suspended tube will be repelled. Bring near the suspended tube a rod of sealing wax rubbed with flannel. The suspended tube is now attracted. Repeat these tests with an electrified rod of sealing wax in the stirrup instead of the glass tube. The electrified

sealing wax will repel the electrified sealing wax, but there will be attraction between the sealing wax and the glass tube.

The experiment illustrates the fact that there are *two kinds of electrification:* one developed by rubbing glass with silk, and the other by rubbing sealing wax with flannel. To the former Benjamin Franklin gave the name *positive electrification;* to the latter, *negative electrification.*

It appears further that bodies charged with the same kind of electrification repel each other, and bodies charged with unlike electrifications attract each other. Hence the law:

Like electrical charges repel each other; unlike electrical charges attract each other.

410. The Electroscope. — An instrument for detecting electrification and for determining its kind is called an *electroscope.* Of the many forms proposed the one shown in section in Fig. 356 is typical. The indicating system consists of a rigid piece of brass *B*, to which is attached a narrow strip of gold leaf *G*. This system is supported by a block of sulphur *I*, which in turn is suspended by a rod fitting tightly in a block of ebonite *E*. A charging wire *W* passes through the ebonite and is bent at right angles at the bottom. By rotating the upper bent end of *W*, the arm at the bottom may be brought in contact with the brass strip for charging. Instead of a ball the supporting rod may end in a round flat plate. When the instrument has flat glass sides, the gold leaf may be projected on the screen with a lantern.

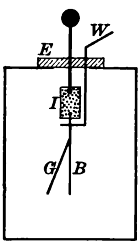


FIGURE 356. — ELECTROSCOPE.

411. Charging an Electroscope. — To charge an electroscope an instrument called a *proof plane* is needed. It consists of a small metal disk attached to an ebonite handle (Fig. 357). To use it, touch the disk to the electrified body and then apply it to the knob of the electroscope. The angular


FIGURE 357. — PROOF PLANE.

separation of the foil from the stem will indicate the intensity of the electric charge imparted. This method is known as *charging by contact* in distinction from *charging by induction* to be described later.

412. Testing for Kind of Electrification. — Charge the electroscope, by means of the proof plane, with the kind of electrification to be identified, until the leaf diverges a moderate distance. Then apply a charge from a glass rod electrified by rubbing with silk. If the divergence increases, the first charge was positive; if not, recharge the electroscope from the unknown and apply a charge taken from a stick of sealing wax excited by friction with flannel. No certain conclusion can be drawn unless an increased divergence is obtained.

413. Conductors and Nonconductors. — Fasten a smooth metal button to a rod of sealing wax and connect the button with the knob of the electroscope by a fine copper wire, 50 to 100 cm. long. Hold the sealing wax in the hand and touch the button with an electrified glass rod. The divergence of the leaf indicates that it is electrified. Repeat the experiment, using a silk thread instead of the wire; no effect is produced on the electroscope. Now wet the thread with water and apply the electrified rod; the effect is the same as when the wire was used.

It is clear from these experiments that electric charges pass readily from one point to another along copper wire, but do not pass along dry silk thread. It is therefore customary to divide substances into two classes, *conductors* and *nonconductors*, or *insulators*, according to the facility with which electric charges pass in them from point to point. In the former if one point of the body is electrified by any means, the electrification spreads over the whole body, but in a nonconductor the electrification is confined to the vicinity of the point where it is excited. Substances differ greatly in their conductivity, so that it is

not possible to divide them sharply into two classes. There is no substance that is a perfect conductor; neither is there any that affords perfect insulation. Metals, carbon, and the solution of some acids and salts are the best conductors. Among the best insulators are paraffin, turpentine, silk, sealing wax, India rubber, gutta-percha, dry glass, porcelain, mica, shellac, spun quartz fibers, and liquid oxygen. Some insulators, like glass, become good conductors when heated to a semi-fluid condition.

II. ELECTROSTATIC INDUCTION

414. Electrification by Induction. — Rub a glass tube with silk and bring it near the top of an electroscope. The leaves begin to diverge when the tube is some distance from the knob (Fig. 358) and the amount of divergence increases as the tube approaches. When the tube is removed the leaves collapse.

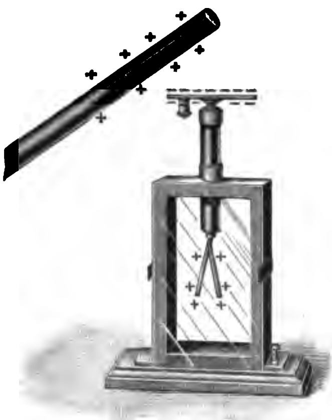


FIGURE 358. — ELECTRIFICATION BY INDUCTION.

Since the leaves do not remain apart, it is evident that there has been no transfer of electrification from the tube to the electroscope. The electrification produced in the electroscope when the electrified body is brought near it is owing to *electrostatic induction*. This form of electrification is only a temporary one and it is brought about by the presence of a charged body in its vicinity.

415. Sign of the Induced Charges. — Lay a smooth metallic ball on a dry plate of glass. Connect it with the knob of the electro-

scope by means of a stout wire with an insulating handle (Fig. 359). The ball and the electroscope now form one continuous conductor. Bring near the ball an electrified glass tube; the leaves of the electroscope diverge. Before withdrawing the excited tube, remove the wire conductor. The electroscope remains charged, and it will be found to be positive. A similar test made of the ball will show that it is negatively charged.

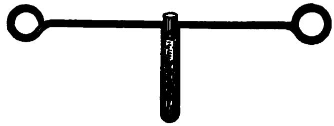


FIGURE 359. — WIRE WITH INSULATING HANDLE.

Hence, we learn that *when an electrified body is brought near an object it induces the opposite kind of electrification on the side next it and the same kind on the remote side.*

416. Charging an Electroscope by Induction. — Hold a finger on the ball of the electroscope and bring near it an electrified glass tube (Fig. 360). Remove the finger before taking away the tube; the electroscope will be charged negatively. If a stick of electrified sealing wax be used instead of the glass tube, the electroscope will be charged positively.

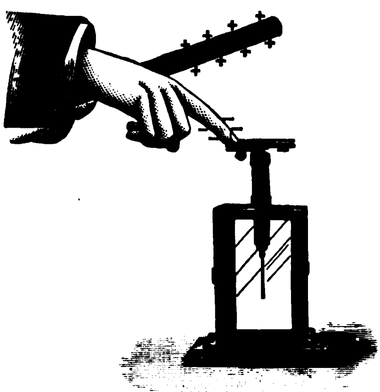


FIGURE 360. — CHARGING ELECTROSCOPE BY INDUCTION.

417. Equality of the Two Charges. — Using the apparatus of § 415, charge the ball and the electroscope by induction. Then replace the wire conductor. The leaves of the electroscope will collapse, showing that the electroscope is discharged. If the ball be tested, it will also be found to be discharged. Hence,

The inducing and the induced charges are equal to each other.

III. ELECTRICAL DISTRIBUTION

418. The Charge on the Outside of a Conductor. — Place a round metallic vessel of about one liter capacity on an insulated support (Fig. 361). Electrify strongly and test in succession both the inner and the outer surface, using a proof plane to convey the charge to the electroscope. The inner surface will give no sign of electrification.

FIGURE 361. — CHARGE ON OUTSIDE.

Hence, it appears that *the electrical charge of a conductor is confined to its outer surface.*

419. Effect of Shape. — Charge electrically an insulated egg-shaped conductor (Fig. 362). Touch the proof plane to the large end, and convey the charge to the electroscope. Notice the amount of divergence of the leaves. Test the side and the small end of the conductor in the same way. The greatest divergence of the leaves will be produced by the charge from the small end and the least from the sides.

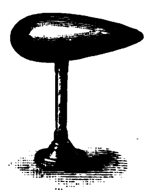


FIGURE 362. — SURFACE DENSITY DEPENDENT ON CURVATURE.

The experiment shows that the surface density is greatest at the small end of the conductor.

By *surface density* is meant the quantity of electrification on a unit area of the surface of the conductor.

The distribution of the charge is, therefore, affected by the shape of the conductor, the surface density being greater the greater the curvature.

420. Action of Points. — Attach a sharp-pointed rod to one pole of an electrical machine (§ 433), and suspend two pith balls from the same pole. When the machine is worked there will be little or no separation of the pith balls. Hold a lighted candle near the pointed rod; the candle flame will be blown away as by a stiff breeze (Fig. 363).

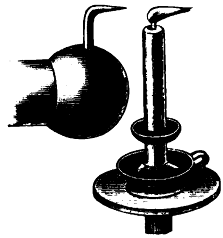


FIGURE 363. — FLAME BLOWN AWAY BY DISCHARGE FROM POINT.

The experiment shows that an electric charge is carried off by pointed conductors. This conclusion might have been drawn from the preceding experiment. When the curvature of the egg-shaped conductor becomes very great so that the surface becomes pointed, the surface density also becomes great and there is an intense field of electric force in the immediate neighborhood. The air particles touching the point become heavily charged and are then repelled; other particles take their place and are in turn repelled and form an *electrical wind.* The conductor gives up its charge to the repelled particles of air.

Questions

1. When a charge is conveyed by a proof plane to an electroscope, does the proof plane give up its entire charge?

2. Why will not an electroscope remain charged indefinitely?

3. If the ball of an electroscope were hollow with an aperture so that the charged proof plane could be introduced, would any charge remain on the proof plane after touching the inside of the ball?

4. Will dust have any effect on the working of electrical apparatus?

5. Why should electrical apparatus be warmer than the room if we are to get good results in electrostatic experiments?

6. Why does electrostatic apparatus work better in cold weather than in warm?

7. Place an electroscope in a cage of fine wire netting. Why is it not affected by an electrified glass rod held near it?

8. Why does not a metal rod held in the hand and rubbed with silk show electrification?

9. With a positively charged globe, how could another insulated globe be charged without reducing the charge on the first one?

10. In charging an electroscope by induction, why must the finger be withdrawn before removing the inducing charge?

IV. ELECTRIC POTENTIAL AND CAPACITY

421. The Unit of Electrification or Charge. — Imagine two minute bodies similarly charged with equal quantities of electricity. They will repel each other. If the two equal and similar charges are one centimeter apart in air, and if they repel each other with a force of one dyne, then the charges are both unity. *The electrostatic unit of quantity is that quantity which will repel an equal and similar quantity at a distance of one centimeter in air with a force of one dyne.* It is necessary to say "in air" because, as will be seen later, the force between two charged bodies depends on the nature of the medium between them (§ 427).

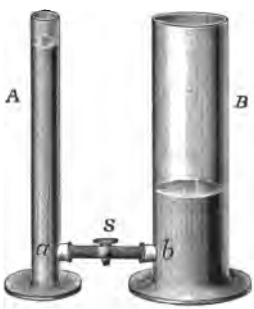


FIGURE 364.— ILLUSTRATING POTENTIAL DIFFERENCE.

This electrostatic unit is very small and has no name. In practice, a larger unit, called the *coulomb*, is employed. It is equal to 3×10^9 electrostatic units.

422. Potential Difference. — The analogy between *pressure* in hydrostatics and *potential* in electrostatics is a very convenient and helpful one. Water will flow from the tank *A* to the tank *B* (Fig. 364) when the stopcock *S* in the connecting pipe is open if the hydrostatic pressure at *a* is greater than at *b*; and the flow is attributed directly to this difference of pressure.

In the same way, if there is a flow of positive electricity from A to B when the two conductors are connected by a conducting wire r (Fig. 365), the electrical potential is said to be higher at A than at B, and the difference of electrical potential between A and B is assigned as the cause of the flow. In both cases the flow is in the direction of the difference of pressure or difference of potential, irrespective of the fact that B may already contain more water because of its large cross section, or a greater electric charge because of its larger capacity (§ 425).

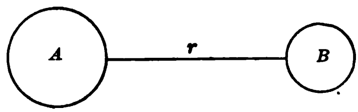


FIGURE 365. — CONDUCTOR A OF HIGHER POTENTIAL THAN CONDUCTOR B.

If the electric charge in a system of connected conductors is in a stationary or static condition, there is then no potential difference between different points of the system.

The *potential difference* between two conductors is measured by the work done in carrying a unit electric charge from the one to the other.

423. Unit Potential Difference. — There is unit potential difference between two conductors when one erg of work is required to transfer the unit electric charge from one conductor to the other. This is called the *absolute* unit; for practical purposes it has been found more convenient to employ a unit of potential difference (P. D.), which is $\frac{1}{300}$ of the absolute unit, and which is called the *volt*, in honor of the Italian physicist, Alessandro Volta.

424. Zero Potential. — In measuring the potential difference between a conductor and the earth, the potential of the earth is assumed to be zero. The potential difference is then numerically the *potential of the conductor*. If a

conductor of positive potential be connected with the earth by an electric conductor, the positive charge will flow to the earth. If the conductor has a negative potential, the flow of the positive quantity will be in the other direction.

425. Electrostatic Capacity. — If water be poured into a cylindrical jar until it is 10 cm. deep, the pressure on the bottom of the jar is 10 g. of force per square centimeter. If the depth of the water be increased to 20 cm., the pressure will be 20 g. of force per square centimeter (§ 53). It thus appears that there is a constant relation between the quantity of water Q and the pressure P; that is, $\frac{Q}{P} = C$, a constant.

Again, if a gas tank be filled with gas at atmospheric pressure, it will exert a pressure of 1033 g. of force per square centimeter (§ 81). If twice as much gas be pumped into the tank, the pressure by Boyle's law (§ 87) will be doubled at the same temperature; that is, there is a constant relation between the quantity of gas Q and the pressure P of the gas in the tank, or $\frac{Q}{P} = C$, a constant as before.

In the same way, if an electric charge be given to an insulated conductor, its potential will be raised above that of the earth. If the charge be doubled, the potential difference between the conductor and the earth will also be doubled. Precisely as in the case of the water and of the gas, there is a constant relation between the amount of the charge Q and the potential difference V between the conductor and the earth; that is, $\frac{Q}{V} = C$. This ratio or constant C is the *electrostatic capacity* of the conductor.

If $V = 1$, then $C = Q$; from which it follows that *the*

electrostatic capacity of a conductor is equal to the charge required to raise its potential from zero to unity.

From $\frac{Q}{V} = C$ we have $Q = CV$, and $V = \frac{Q}{C}$. (Equation 34)

426. Condensers. — Support a metal plate in a vertical position on an insulating base (Fig. 366). Connect it to the knob of an electroscope by a fine copper wire. Charge the plate until the leaves of the electroscope show a wide divergence. Now bring an uninsulated conducting plate near the charged one and parallel to it. The divergence of the leaves will decrease; remove the uninsulated plate and the divergence will increase again.

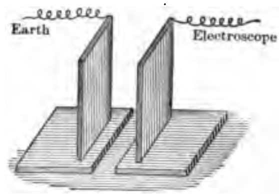


FIGURE 366. — CONDENSER EFFECT.

The capacity of an insulated conductor is increased by the presence of another conductor connected with the earth. The effect of this latter conductor is to decrease the potential to which a given charge will raise the insulated one. Such an arrangement of parallel conductors separated by an insulator or *dielectric* is called a *condenser.*

A condenser is a device which greatly increases the charge on a conductor without increasing its potential. In other words, the plate connected with the earth greatly increases the capacity of the insulated conductor.

427. Influence of the Dielectric. — Charge the apparatus of the last experiment, with the uninsulated plate at a distance of about 5 cm. from the charged plate and parallel to it, thrust suddenly between the two a cake of clean paraffin as large as the metal plates or larger, and from 2 to 4 cm. thick. Note that the leaf of the electroscope (Fig. 356) collapses slightly. Remove the paraffin quickly, and the divergence will increase again. A cake of sulphur will produce a more marked effect on the divergence of the leaf.

The presence of the paraffin or the sulphur increases the capacity of the condenser and, hence, decreases its potential, the charge remaining the same. Paraffin and sulphur, as examples of dielectrics, are said to have a larger *dielectric capacity* or *dielectric constant* than air. Glass has a dielectric capacity from four to ten times greater than air.

FIGURE 367. — LEYDEN JAR.

428. The Leyden Jar is a common and convenient form of condenser. It consists of a glass jar coated part way up, both inside and outside, with tin-foil (Fig. 367). Through the wooden or ebonite stopper passes a brass rod, terminating on the outside in a ball and on the inside in a metallic chain which reaches the bottom of the jar. The glass is the dielectric separating the two tin-foil conducting surfaces.

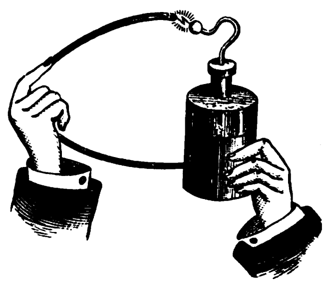


FIGURE 368. — DISCHARGING A LEYDEN JAR.

429. Charging and Discharging a Jar. — To charge a Leyden jar connect the outer surface to one pole of an electrical machine (§ 433), either by a metallic conductor or by holding the jar in the hand. Hold the ball against the other pole. To discharge a Leyden jar bend a wire into the form of the letter V. With one end of the wire touching the *outer* surface of the jar (Fig. 368), bring the other around near the ball, and the discharge will take place.

430. Seat of Charge. — Charge a Leyden jar made with movable metallic coatings (Fig. 369) and set it on an insulating stand. Lift out the inner coating, and then, taking the top of the glass vessel in one hand, remove the outer coating with the other. The coatings now exhibit no sign of electrification. Bring the glass vessel near a pile of pith balls; they will be attracted to it, showing that the glass is electrified. Reach over the rim with the thumb and forefinger and touch the glass. A slight discharge may be heard. Now build up the jar by putting the parts together; the jar will still be highly electrified and may be discharged in the usual way.

FIGURE 369. — SEAT OF THE CHARGE.

This experiment was devised by Franklin; it seems that electrification is a phenomenon of the glass, and that the metallic coatings serve merely as conductors, making it possible to discharge all parts of the glass at once. Some claim that the moisture condensed on the glass acts as a conductor when the metallic coatings are removed.

431. Theory of the Leyden Jar. — A Leyden jar may be perforated by overcharging, may be discharged by heating, and if heavily charged is not completely discharged by connecting the two coatings; if left standing a few seconds, the two coatings gradually acquire a small potential difference and a second small discharge may be obtained, known as the *residual charge*. It appears, therefore, that the glass of a charged jar is strained or distorted; like a twisted glass fiber, it does not return at once to its normal state when released.

The two surfaces of the glass are oppositely electrified, the one charge acting inductively through the glass and producing the opposite electrification on the other surface. The two charges are held inductively and are said to be

"bound," in distinction from the charge on an insulated conductor, which is said to be "free."

Questions

1. Will a charged Leyden jar be discharged by touching the knob while the jar rests on a sheet of hard rubber?

2. Will a Leyden jar be appreciably charged by applying charges to the knob while the jar rests on a sheet of hard rubber?

3. In discharging a Leyden jar with a bent wire, why not touch the wire to the knob before touching the outside surface?

4. Cuneus tried to charge a bowl of water by holding it in his hand, while the chain of an electrical machine dipped into the water. When he lifted the chain with the other hand he got a shock. Why?

5. Explain why a small metal ball suspended by a silk thread between two bodies, the two being near together and charged, one negatively and the other positively, flies back and forth between the two bodies.

V. ELECTRICAL MACHINES

432. The Electrophorus. — The simplest induction electrical machine is the *electrophorus* (Fig. 370), invented by Volta. A cake of resin or disk of vulcanite A rests in a metallic base B. Another metallic disk or cover C is provided with an insulating handle D. The resin or vulcanite is electrified by rubbing with dry flannel or striking with a catskin, and the metal disk is then placed on it. Since the cover touches the nonconducting resin or vulcanite A in a few points only, the negative charge due to the friction is not removed. The two disks with the film of air between them form a condenser (§ 426) of great capacity.

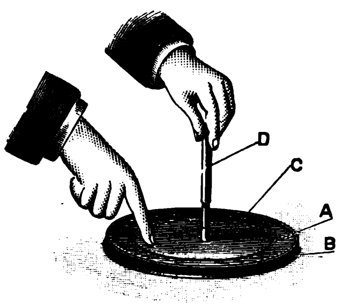


FIGURE 370. — ELECTROPHORUS.

Touch the cover momentarily with the finger, and the repelled negative charge passes to the earth, leaving the cover at zero potential. Lift it by the insulating handle, the positive charge becomes free (§ 431), and a spark may be drawn by holding the finger near it. This operation may be repeated an indefinite number of times without sensibly reducing the charge on the vulcanite.

When the cover is lifted by the insulating handle, work is done against the electrical attraction between the negative charge on the vulcanite and the positive on the cover. The energy of the charged cover represents this work.

The electrophorus is, therefore, a device for transforming energy in some other form into the energy of electric charges.

433. Influence Electrical Machines. — There are many influence or induction electrical machines, but it will suffice to describe only one, as the principle is always the same.

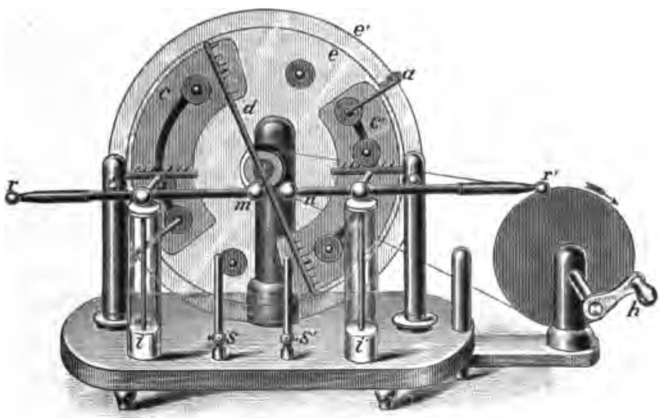


FIGURE 371. — TOEPLER-HOLTZ MACHINE.

The Holtz machine, as modified by Toepler and Voss, is illustrated in Fig. 371. There are two glass plates, e' and e, about 5 mm. apart, the former stationary and the

latter turning about an insulated axle by means of the crank *h* and a belt. The stationary plate supports at the back two paper sectors, *c* and *c'*, called *armatures*. Between them and the stationary plate *e'* are disks of tin-foil connected by a narrow strip of the same material. The disks are electrically connected with two bent metal arms, *a* and *a'* (opposite *a*), which carry at the other end tinsel brushes long enough to rub against low brass buttons cemented to small tin-foil disks, called *carriers*, on the front of the *revolving* plate. Opposite the paper sectors and facing them are two metal rods with several sharp-pointed teeth set close to the revolving plate, but not touching the metal buttons and carriers. The diagonal neutralizing rod *d* has tinsel brushes in addition to the sharp points. The two insulated conductors, terminating in the balls, *m* and *n*, have their capacity increased by connection with the inner coating of two small Leyden jars, *i* and *i'*; the outer coatings are connected under the base of the machine.

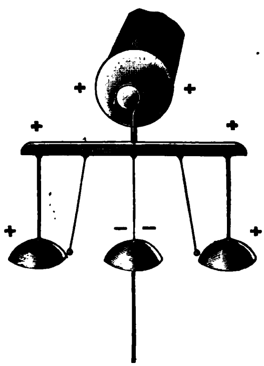


FIGURE 372. — BELLS RUNG BY ELECTRIFICATION.

There are so many varieties of induction machines, and the explanation of their operation is so involved and uncertain, that we shall leave it for those interested in the subject to look it up in special books on electricity.

434. Experiments with Electrical Machines. — 1. *Attraction and repulsion.* Place a number of bits of paper on the cover of a charged electrophorus. Lift it by the insulating handle. The charged pieces of paper fly off the plate.

Three bells are suspended from a metal bar (Fig. 372). The

middle one is insulated from the bar; the others are suspended by chains. Connect the bar to one pole of an electrical machine and the middle bell to the other. The small brass balls between the bells are suspended by silk cords; they swing to and fro between the bells, carrying positive charges in one direction and negative in the other. This apparatus, called the electrical chimes, is of interest because it was employed by Franklin in his lightning experiments to announce the electrification of the cord leading to the kite (§ 435).

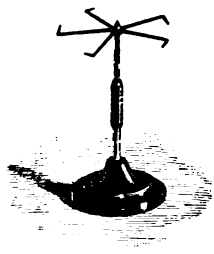


FIGURE 373. — ELECTRICAL TOURNIQUET.

2. *Discharge by points.* Connect an electrical tourniquet (Fig. 373) to one of the conductors of an electrical machine, the other conductor being grounded. When the machine is turned, the whirl rotates rapidly (§ 420).

3. *Mechanical effects.* Hold a piece of cardboard between the discharge balls of an electrical machine. It will be perforated by a spark and the holes will be burred out on both sides. A thin dry glass plate, or a thin test tube over a sharp point, may be perforated by a heavy discharge.

4. *Heating effects.* Charge a Leyden jar and connect its outer coating with a gas burner by a chain or wire. Turn on the gas and bring the ball of the jar near enough to the opening in the burner to allow a spark to pass. The gas will be lighted by the discharge.

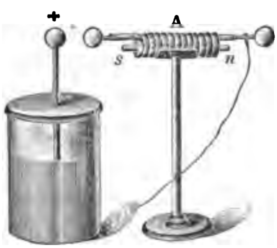


FIGURE 374. — NEEDLE MAGNETIZED BY ELECTRIC DISCHARGE.

Fill a gas pistol with a mixture of coal gas and air. Discharge a Leyden jar through the mixture. It will explode and the cork or ball will be shot out with some violence.

Magnetic effects. Wind insulated copper wire around a small glass tube (Fig. 374), and place inside the tube a piece of darning needle. Discharge a Leyden jar through the wire. The needle will be magnetized. A similar effect may be produced by placing a large sewing needle across a strip of tin-foil forming a part of the discharge circuit of a Leyden jar.

VI. ATMOSPHERIC ELECTRICITY

435. Lightning. — Franklin demonstrated in 1752 that lightning is identical with the electric spark. He sent up a kite during a passing storm, and found that as soon as the hempen string became wet, long sparks could be drawn from a key attached to it, Leyden jars could be charged, and other effects characteristic of static electrification could be produced. The string was not held in the hand directly, but by a silk ribbon tied to it for safety.

FIGURE 375. — LIGHTNING DISCHARGE.

Lightning flashes are discharges between oppositely charged bodies. They occur either between two clouds or between a cloud and the earth (Fig 375). The rise of potential in a cloud causes a charge to accumulate on the earth beneath it. If the stress in the air reaches a value of about 400 dynes per square centimeter, the air breaks down, or is ruptured, like any other dielectric, and the two opposite charges unite in a long zigzag flash. A lightning flash allows the strained medium to return to equilibrium. The coming together of the air surfaces, which are separated in the rupture, produces a violent crash of *thunder*. If the path of the flash be long and zigzag, the observer will hear successive sounds from differ-

Benjamin Franklin (1706–1790) was born at Boston, Massachusetts. In his twentieth year he was apprenticed to his elder brother in the printing business. When forty years of age he saw some electrical experiments performed with a glass tube. These excited his curiosity and he began experimenting for himself. In less than a year he had discovered the discharging effects of points and worked out a theory of electricity, known as the "one-fluid theory." He explained the charged Leyden jar, established the identity of lightning and the electric spark, invented an electric machine, and introduced the lightning rod as a protection against lightning. He was distinguished as a statesman, diplomatist, and scientist. He founded the American Philosophical Society and the University of Pennsylvania.

ent parts of the path as a crackling rattle ; then the echoes from other clouds will come rolling in afterwards. The duration of a lightning flash is never more than $\frac{1}{100000}$ of a second. If it lasted much longer, its intensity is so great that it would be blinding.

436. The Lightning Rod. — Support two round metal plates, *T* and *T'*, one above the other and a few centimeters apart (Fig. 376). The upper plate must be carefully insulated except from the pole of the electrical machine and the inner coating of a Leyden jar *L*. Two of the short rods on the lower plate terminate in small balls; the other and shortest one is pointed. When the machine is worked, the tension between the plates increases, but it is difficult to make a spark pass; if one does pass, it will strike the pointed rod.

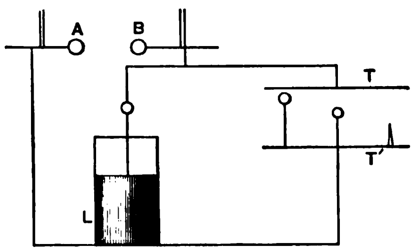


FIGURE 376. — PROTECTION BY POINTED ROD.

The experiment illustrates the protection afforded by a pointed conductor.

A lightning rod should conform to the following requirements :

First. It should be perfectly continuous, of sufficient size to resist fusion, and made preferably of strands of wire twisted together as a cable. Iron cables are as good as copper ones.

Second. The upper end should terminate in points and should be higher than adjacent parts of the building. The lower end should pass down into the earth until it enters a moist conducting stratum.

Third. The rod should be fastened to the building without insulators, and all metal parts of the roof should

be connected with the main conductor. It is better to have two or three descending rods than one, and all the points and rods should be connected together as a network.

The protection afforded by lightning rods, properly erected, is abundantly proven by the statistics of mutual fire insurance companies for buildings in the country.

437. Oscillatory Discharge. — When a Leyden jar is highly charged, the potential difference between its coatings increases until the dielectric between the discharge terminals suddenly breaks down and a spark passes. This discharge usually consists of several oscillations or to-and-fro discharges, like the vibrations of an elastic system or the surges of a mass of water after sudden release from pressure. Imagine a tank with a partition across the middle and filled on one side with water. If a small hole be made in the partition near the bottom, the water will slowly reach the same level on both sides without agitation; but if the partition be suddenly removed, the first violent subsidence will be succeeded by a return surge, and the to-and-fro motion of the water will continue with decreasing violence until the energy is all expended.

A series of similar surges occurs when a condenser is suddenly discharged by the breaking down of the dielectric. The oscillatory character of such electric discharges was discovered by Joseph Henry in 1842. Its importance has been recognized only in recent times. Similar electric oscillations probably take place in some lightning flashes.

438. The Aurora. — The *aurora* is due to silent discharges in the upper regions of the atmosphere. Within the arctic circle it occurs almost nightly, and sometimes with indescribable splendor. The illumination of the aurora is due to positive discharges passing from the higher regions of the atmosphere to the earth. In our latitude these silent streamers in the atmosphere are infrequent. When they do occur they are accompanied by great disturbances of the earth's magnetism and by earth currents. Such magnetic disturbances sometimes occur at the same time in widely separated portions of the earth.

CHAPTER XII

ELECTRIC CURRENTS

I. VOLTAIC CELLS

439. An Electric Current. — The discharge of a condenser through a wire produces in and around the wire a state called an *electric current.* If by any arrangement electricity could be supplied to the condenser as fast as it is conveyed away through the wire, a continuous current would be produced. Any arrangement by which the ends of a conducting wire are kept at different potentials will insure the flow of a continuous current through it.

It is analogous to the flow of heat through a metal rod if one end is kept at a higher temperature than the other, the heat flowing from the hotter to the colder end. So also a stream of water flows through a section of pipe if the pressure at one end is maintained higher than at the other. It is customary to consider the electric current as flowing from positive to negative, that is, from higher potential to lower.

One of the simplest means of maintaining a potential difference between the terminals of a conductor is the primary or voltaic cell.

440. The Voltaic Cell. — Support a heavy strip of zinc and one of sheet copper (Fig. 377) in dilute sulphuric acid (one part acid to twenty of water). After the zinc has been in the acid a short time, it should be *amalgamated* by rubbing it with mercury. There will be no apparent change when the plates are replaced in the acid, until

the two are connected with a copper wire; a multitude of bubbles of hydrogen gas will then immediately be given off at the surface of the copper plate. The action ceases as soon as the wires are disconnected. If the action is continued for some time, the zinc will waste away, while the copper is not affected.

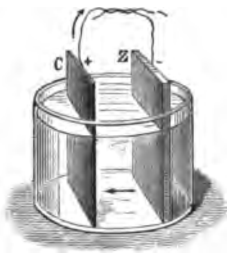


FIGURE 377. — VOLTAIC CELL.

Such a combination of two conductors, immersed in a compound liquid, called an *electrolyte*, which is capable of reacting chemically with one of the conductors, is called a *voltaic cell*. The name is derived from Volta of Padua, who first described such a cell in 1800.

441. Plates Electrically Charged. — In a condensing electroscope the ball at the top is replaced by a brass disk coated with thin shellac varnish as an insulator. Resting on it is a second disk to which is fitted an insulating handle. The two disks with the shellac varnish between them form a condenser of considerable capacity.

Connect the wire leading from the copper plate of two or three voltaic cells C in series (§ 473) to the lower disk A of the electroscope, and the wire from the zinc plate to the upper disk B (Fig. 378). Disconnect the wires, handling them one at a time by means of a good insulator so as not to discharge the condenser, and then lift the top disk. The leaf L of the electroscope will diverge, and a test with an electrified glass rod will show that the electroscope is charged positively. This positive charge was derived from the copper strip of the cell. Repeat the experiment with the zinc plate connected to the lower disk; the result will be a negative charge on the gold leaf.

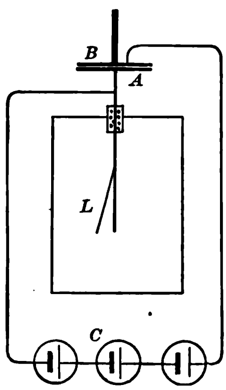


FIGURE 378. — PLATES OF A VOLTAIC CELL CHARGED.

It is clear from this experiment that the *plates of a voltaic cell and the wires leading from them are electrically charged, the copper positively and the zinc negatively.* The conducting rods, plates, or cylinders in a voltaic cell are called *electrodes*, the *copper* the *positive electrode* and the *zinc* the *negative electrode.* The electric current leaves the electrolyte by the positive electrode and enters it by the negative.

442. The Circuit. — The *circuit* of a voltaic cell comprises the entire path traversed by the current, including the electrodes and the liquid in the cell as well as the external conductor. *Closing the circuit* means joining the two electrodes by a conductor; *breaking* or *opening the circuit* is disconnecting them. So when the circuit is broken at any point by a key, a switch, or a push button, the circuit is said to be *open;* when the key or switch is closed, so as to make a continuous path for the current, the circuit is said to be *closed.* The flow of current in the external circuit is from the positive electrode (copper) to the negative (zinc), and in the internal part of the circuit from the negative electrode to the positive (Fig. 377).

443. Electrochemical Actions in a Voltaic Cell. — The theory of dissociation furnishes an explanation of the manner in which an electric current is conducted through a liquid. It is briefly as follows: When a chemical compound such as sulphuric acid (H_2SO_4),* for example, is dissolved in water, some of the molecules at least split into two parts ($\overset{++}{H_2}$ and $\overset{--}{SO_4}$), one part having a positive electrical charge and the other a negative one.

The two parts of the dissociated substance with their

* Each molecule of sulphuric acid is composed of two atoms of hydrogen (H_2), one of sulphur (S), and four of oxygen (O_4).

electrical charges are called *ions* (from a Greek word meaning *to go*). An *electrolyte* is a compound capable of such dissociation into ions. It conducts electricity only by means of the migration of the ions resulting from the splitting in two of the molecules. The separated ions convey their charges with a slow and measurable velocity through the liquid. Electropositive ions, such as zinc and hydrogen, carry positive charges in one direction, electronegative ions, such as "sulphion" ($\overset{--}{SO_4}$), carry negative charges in the opposite direction, and the sum of the two kinds of charges carried through the liquid per second is the measure of the current.

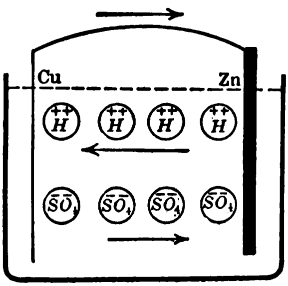


FIGURE 379.—SECTION OF CELL WITH IONS.

Figure 379 represents a section of a voltaic cell with the electropositive and electronegative ions. When the circuit is closed and a current flows, zinc from the zinc plate enters the solution as electropositive ions ($\overset{++}{Zn}$), while the positive hydrogen ions migrate toward the copper plate or cathode, and the sulphions toward the zinc plate. The $\overset{--}{SO_4}$ ions carry negative charges to the zinc plate, so that it becomes charged negatively, while the $\overset{++}{H_2}$ ions carry positive charges to the copper plate and it becomes charged positively. Zinc from the zinc plate thus goes into solution as zinc sulphate ($ZnSO_4$), and hydrogen when it has given up its positive charge is set free as gaseous hydrogen on the copper plate. Some prefer to say that when the zinc ions with their positive charge leave the zinc plate, the equivalent negative is left behind

to charge the zinc electrode. The zinc ions unite with the sulphions to form neutral zinc sulphate. Thus, while the zinc *ions* are electropositive and carry positive charges, the zinc *plate* is charged negatively.

444. Electromotive Force. — Imagine a rotary pump which produces a difference of pressure between its inlet and its outlet. Such a pump may cause water to circulate through a system of horizontal pipes against friction. In any portion of the pipe system the force producing the flow is the difference of water pressure between the ends of that portion. But the force is all applied at the pump, and this produces a pressure throughout the whole circuit. A voltaic cell is an electric generator analogous to such a pump.

A voltaic cell generates electric pressure called *electromotive force.* It does not generate electricity any more than the pump generates water, but it supplies the electric pressure to set electricity flowing. This electromotive force (E.M.F.) is numerically equal to the work which must be done to transport a unit quantity of electricity around the external circuit from *A* to *B*, through the zinc plate to *Z*, from *Z* through the liquid *C*, and thence back to *A* (Fig. 380). Work is done in this transfer, because all conductors offer resistance to the passage of a current. The energy thus expended goes to heat the conductor. A voltaic cell is thus a device for transforming chemical energy into the energy of an electric current.

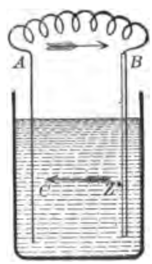


FIGURE 380. — CIRCUIT THROUGH VOLTAIC CELL.

445. Difference of Potential. — The difference of potential between two points, *A* and *B*, on the external conducting circuit is the work done in carrying a unit quantity of

electricity from the one point to the other. The difference of potential between the electrodes of a voltaic cell when the circuit is closed is less than the E.M.F. of the cell by the work done in transferring unit quantity of electricity through the electrolyte. If E denotes this potential difference and Q the quantity conveyed, then the whole work done is the product EQ. But the quantity conveyed by a conductor per second is called the *strength of current*, I. The energy transformed in a conductor, therefore, when current I flows through it, under an electric pressure or potential difference of E units between its ends, is EI ergs per second.

446. Detection of Current. — Solder a copper wire to each of the strips of a voltaic cell, and connect the wires with some form of key to close the circuit. Stretch a portion of the wire over a mounted magnetic needle (Fig. 381), holding it parallel to it and as near as possible without touching. Now close the circuit; the needle is deflected, and comes to rest at an angle with the wire. Next form a rectangular loop of the wire, and place the needle within it. A greater deflection is now obtained. If a loop of several turns is formed, the deflection is still greater.

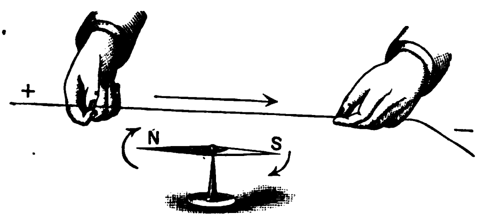


FIGURE 381. — DEFLECTION OF NEEDLE BY CURRENT.

A magnetic needle employed in this way becomes a *galvanoscope*, a detector of electric currents. This experiment, first performed by Oersted in 1819, shows that the region around the wire has magnetic properties during the flow of electricity through the wire. In other words, it is a magnetic field (§ 398).

Hans Christian Oersted (1777–1851) was born at Rudkjöbing, Denmark, and received his education at the University of Copenhagen, afterward becoming professor in the University and polytechnic school of that city. It was while holding this position that he discovered the action of the electric current on the magnetic needle, thus establishing the connection between electricity and magnetism which had long been sought by scientists. He also discovered that this magnetic action of the electric current takes place freely through a great many substances. Oersted wrote extensively for newspapers and magazines in an endeavor to make science popular.

447. Relation between the Direction of the Current and the Direction of Deflection. — Making use of the apparatus of § 446, compare the direction of the current through the wire with that in which the north pole of the needle turns. Cause the current to pass in the reverse direction over the needle; the deflection is reversed. Now hold the wire below the needle, and the direction of deflection is again reversed as compared with the deflection when the wire is held above the magnetic needle.

The direction of the deflection may always be predicted by the following rule: *Stretch out the right hand along the wire, with the palm turned toward the magnetic needle, and with the current flowing in the direction of the extended fingers. The outstretched thumb will then point in the direction in which the north pole of the needle is deflected* (Fig. 382). By the converse of this rule, the direction of the current may be inferred from the direction in which the needle is deflected.

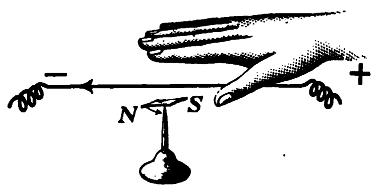


FIGURE 382.—DIRECTION OF DEFLECTION.

448. Local Action. — Place a strip of commercial zinc in dilute sulphuric acid. Hydrogen is liberated during the chemical action, and after a few minutes the zinc becomes black from particles of carbon exposed to view by dissolving away the surface. If the experiment is repeated with zinc amalgamated with mercury, that is, by coating it with an alloy of mercury and zinc, there will be little or no chemical action. A strip of chemically pure zinc acts much like one amalgamated with mercury.

Thus we see that the amalgamation of commercial zinc with mercury changes its properties. If in the experiment with the simple voltaic cell, a galvanoscope is inserted in the circuit both before the zinc has been amalgamated and

afterward, it will be found that a larger deflection will be obtained in the second case.

In a voltaic cell the chemical action which contributes nothing to the current flowing through the circuit is known as *local action*. It is probably due to the presence of carbon, iron, etc., in the zinc; these with the zinc form miniature voltaic cells, the currents flowing around in short circuits from the zinc through the liquid to the foreign particles and back to the zinc again.

This local action is prevented by amalgamating the zinc. The amalgam brings pure zinc to the surface, covers the foreign particles, and above all forms a smooth surface, so that a film of hydrogen clings to it and protects it from chemical action save when the circuit is closed.

449. Polarization. — Connect the poles of a voltaic cell to a galvanoscope and note the deflection. Let the cell remain in circuit with the galvanoscope for some time; the deflection will gradually become less and less. Now stir up the liquid vigorously with a glass rod, inserting the rod between the plates and brushing off the adhering gas bubbles; the deflection will increase nearly to its first value.

FIGURE 383. — TO SHOW POLARIZATION.

Fasten two strips of zinc and two of copper to a square board and immerse them in dilute sulphuric acid (Fig. 383). Join one zinc and one copper strip with a short wire for a few minutes. Then disconnect and join the two coppers to a galvanoscope. The direction of the deflection will be the same as if zinc were used in place of the copper strip coated with hydrogen. The hydrogen-coated copper acts like zinc and tends to produce a current through the electrolyte from it to the copper free from hydrogen.

The diminution in the intensity of the current is due to several causes, but the chief one is the film of hydrogen

which gathers on the copper plate, causing what is known as the *polarization* of the cell. The hydrogen on the positive plate not only introduces more resistance to the flow of the current, but it diminishes the electromotive force to which this flow is due. The presence of hydrogen on the copper plate sets up an inverse E.M.F., which reduces the flow.

450. Remedies for Polarization. — Place enough pure mercury in a quart jar to cover the bottom, and hang above it a piece of sheet zinc. Fill the jar with a nearly saturated solution of salt water, and place in the mercury the exposed end of a copper wire insulated with gutta-percha, the mercury forming the positive electrode of the battery.

If now the circuit is closed through a telegraph sounder (§ 552) of ten or fifteen ohms resistance, the armature will at first be attracted strongly; but in the course of a few minutes it will be released and will be drawn back by the spring. Polarization has then set in to the extent that the current is insufficient to operate the instrument.

Next take a small piece of mercuric chloride ($HgCl_2$) no larger than the head of a pin, and drop it in on the surface of the mercury. The armature of the sounder will instantly be drawn down, showing that the current has recovered its normal value. The hydrogen has been removed by the chlorine of the mercuric chloride. In a few minutes the chlorine will be exhausted, and polarization will again set in. A little more of the chloride will again restore the activity of the cell. (This experiment was devised several years ago by Mr. D. H. Fitch.)

This illustrates a chemical method of reducing polarization. The hydrogen ions are replaced by others, such as copper or mercury, which do not produce polarization when they are deposited on the positive electrode; or else the positive electrode is surrounded with a chemical which furnishes oxygen or chlorine to unite with the hydrogen before it reaches the electrode. In both cases the electrode is kept nearly free from hydrogen.

451. The Daniell Cell. — *The Daniell cell* in its most common form (Fig. 384) consists of a glass jar containing a saturated solution of copper sulphate ($CuSO_4$), and in it a cylinder *C* of copper, which is cleft down one side. Within the copper cylinder is a porous cup of unglazed earthenware containing a dilute solution of zinc sulphate ($ZnSO_4$). In the porous cup also is the zinc prism *Z*. The copper sulphate must not be allowed to come in contact with the zinc electrode. The porous cup allows the ions to pass through its pores, but it prevents the rapid admixture of the two sulphates.

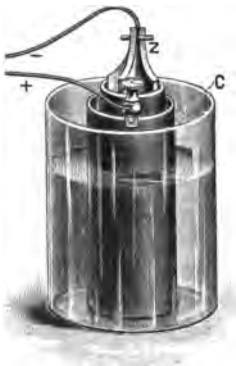


FIGURE 384. — DANIELL CELL.

Both electrolytes undergo partial dissociation into ions; and when the circuit is closed, the zinc and the copper ions both travel toward the copper electrode. The zinc ions do not reach the copper, because zinc in copper sulphate replaces copper, forming zinc sulphate. The result is the formation of zinc sulphate at the zinc electrode and the deposition of metallic copper on the copper electrode. Polarization is completely obviated; and, so long as the circuit is kept closed, the mixing of the electrolytes by diffusion is slight. This cell must not be left on open circuit because the copper sulphate then diffuses until it reaches the zinc and causes a black deposit of copper oxide on it.

452. The Gravity Cell. — This cell (Fig. 385) is a modified Daniell. The porous cup is omitted, and the partial separation of the liquids is secured by difference in density. The copper electrode *C* is placed at the bottom in saturated

copper sulphate *B*, while the zinc *Z* is suspended near the top in a weak solution of zinc sulphate *A*, floating on top of the copper sulphate. The zinc should never be placed in the solution of copper sulphate. The saturated copper sulphate is more dense than the dilute zinc salt, and so remains at the bottom, except as it slowly diffuses upward.

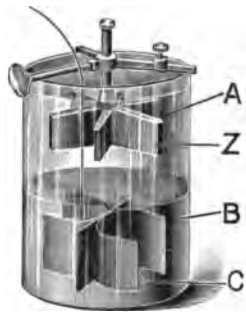


FIGURE 385. — THE GRAVITY CELL.

453. The Leclanché Cell consists of a glass vessel containing a saturated solution of ammonium chloride (sal ammoniac) in which stands a zinc rod and a porous cup (Fig. 386). In this porous cup is a bar of carbon very tightly packed in a mixture of manganese dioxide and graphite, or granulated carbon.

The zinc is acted on by the chlorine of the ammonium chloride, liberating ammonia and hydrogen. The ammonia in part dissolves in the liquid, and in part escapes into the air. The hydrogen is slowly oxidized by the manganese dioxide. The cell is not adapted to continuous use, as the hydrogen is liberated at the positive electrode faster than the oxidation goes on, and hence the cell polarizes. If, however, it is allowed to rest, it recovers from polarization. The Leclanché cell is suitable for ringing electric bells.

FIGURE 386. — THE LECLANCHÉ CELL.

454. The Dry Cell. — The "dry" cell is merely a modified Leclanché specially adapted for use in situations

where cells with a liquid electrolyte cannot be used. The electrodes are zinc and carbon. The cylindrical zinc pot *Z* (Fig. 387) is contained in a cardboard case. It is lined with porous pulp board, which serves the double purpose of taking up part of the liquid content of the cell and separating the solid part from the zinc. The carbon is either round or flat (shown edgeways in the figure). Between the two electrodes is a moist paste or "mix" of varied composition, but containing the essential sal ammoniac, besides granulated carbon, graphite, zinc chloride, and manganese dioxide. The cell is sealed with wax or pitch.

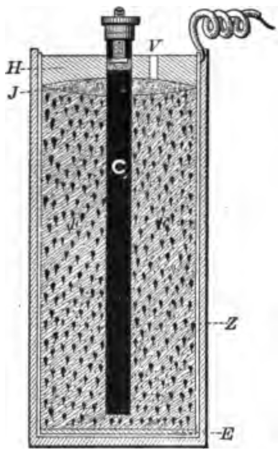


FIGURE 387. — DRY CELL.

Dry cells of the standard size, $2\frac{1}{2} \times 6$ inches, are now made that yield a current of 25 to 30 amperes (§ 469) on short circuit. Smaller sizes in great numbers are used to light miniature electric lights in hand lamps or flash lights. Some fifty millions of "standard" dry cells are now manufactured yearly in the United States, and probably several times that number of small cells for hand lamps. In addition to their application in flash lights, dry cells are much used for ringing bells, running clocks, and working spark coils for ignition in gas engines on boats and automobiles. It should not be forgotten that dry cells must not be left on closed circuit.

455. The Lalande Cell. — The negative is zinc and the exciting liquid is a 30 per cent solution of caustic potash. The zinc dissolves in the alkali, forming zincate of potas-

sium and setting free hydrogen. The positive electrode is a compressed cake of copper oxide, held in a copper frame. The hydrogen reduces the copper oxide to metallic copper. The exciting liquid must be covered with oil to exclude the carbonic acid gas of the air, which converts the alkali into a carbonate. This cell has an electromotive force but little more than half that of the Leclanché, but it is capable of furnishing a large and constant current. On this account it is much used to work railway signals.

II. ELECTROLYSIS

456. Phenomena of Electrolysis. — Thrust platinum wires through the corks closing the ends of a V-tube (Fig. 388). Fill the tube nearly full with a solution of sodium sulphate colored with blue litmus. Pass through it a current for a few minutes. The liquid around the *anode*, where the current enters, will turn red, showing the formation of an acid; the liquid around the *cathode*, where the current leaves the cell, will turn a darker blue, showing the presence of an alkali.

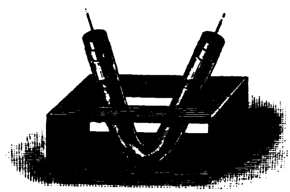


FIGURE 388. — V-TUBE FOR ELECTROLYSIS.

The electric current in its passage through a liquid decomposes it. This process of decomposing a liquid by an electric current Faraday named *electrolysis;* the liquid decomposed he called the *electrolyte;* the parts of the separated electrolyte, *ions*. The current enters the electrolyte by the *anode* (meaning *the way in*) and leaves it by the *cathode* (meaning *the way out*).

457. Electrolysis of Copper Sulphate. — Fill the V-tube of the last experiment about two-thirds full of a solution of copper sulphate. After the circuit has been closed a few minutes, the cathode will be

covered with a deposit of copper, and bubbles of gas will rise from the anode. These bubbles are oxygen.

When copper sulphate is dissolved in water it is dissociated to some extent. If, therefore, electric pressure is applied to the solution through the electrodes, the electropositive ions ($\overset{++}{Cu}$) are set moving from higher to lower potential, while the electronegative ions ($\overset{--}{SO_4}$) carry their negative charges in the opposite direction. The $\overset{++}{Cu}$ ions are therefore driven against the cathode, and, giving up their charges, become metallic copper. The sulphions ($\overset{--}{SO_4}$) go to the anode; and, giving up their charges, they take hydrogen from the water present, forming sulphuric acid (H_2SO_4) and setting free oxygen, which comes off as bubbles of gas. If the anode were copper instead of platinum, the sulphion would unite with it, forming copper sulphate, and copper would be removed from the anode as fast as it is deposited on the cathode. The result of the passage of a current would then be the transfer of copper from the anode to the cathode. This is what takes place in the electrolytic refining of copper.

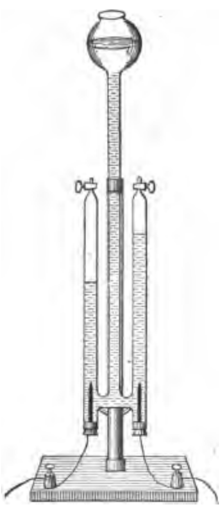


FIGURE 389. — HOFMANN'S APPARATUS FOR ELECTROLYSIS OF WATER.

Thus the passage of an electric current through an electrolyte is accomplished in the same way, whether it is in a voltaic cell or in an electrolytic cell.

458. Electrolysis of Water. — Water appears to have been the *first substance decomposed* by an electric current. Pure

water does not conduct an appreciable current of electricity, but if it is acidulated with a small quantity of sulphuric acid, electrolysis takes place.

In Hofmann's apparatus (Fig. 389) the acidulated water is poured into the bulb at the top, and the air escapes by the glass taps until the tubes are filled. The electrodes at the bottom in the liquid are platinum foil. If a current is sent through the liquid, bubbles of gas will be liberated on the pieces of platinum foil. The gases collecting in the tubes may be examined by letting them escape through the taps. Oxygen will be found at the anode and hydrogen at the cathode; the volume of the hydrogen will be nearly twice that of the oxygen.

459. Laws of Electrolysis. — The following laws of electrolysis were established by Faraday.

I. *The mass of an electrolyte decomposed by an electric current is proportional to the quantity of electricity conveyed through it.*

The mass of an ion liberated in one second is, therefore, proportional to the strength of current.

II. *When the same quantity of electricity is conveyed through different electrolytes, the masses of the different ions set free at the electrodes are proportional to their chemical equivalents.*

By "chemical equivalents" are meant the relative quantities of the ions which are chemically equivalent to one another, or take part in equivalent chemical reactions. Thus, 32.5 g. of zinc or 31.7 g. of copper take the place of one g. of hydrogen in sulphuric acid (H_2SO_4) to form zinc sulphate ($ZnSO_4$) or copper sulphate ($CuSO_4$), respectively.

The first law of electrolysis affords a valuable means of comparing the strength of two electric currents by deter-

mining the relative masses of any ion, such as silver or copper, deposited by the two currents in succession in the same time (§ 469).

460. Electroplating consists in covering bodies with a coating of any metal by means of the electric current. The process may be summarized as follows: Thoroughly clean the surface to remove all fatty matter. Attach the article to the negative electrode of a battery, and suspend it in a solution of some chemical salt of the metal to be deposited. If silver, cyanide of silver dissolved in cyanide of potassium is used; if copper, sulphate of copper. To maintain the strength of the solution a piece of the metal of the kind to be deposited is attached to the positive electrode of the battery and immersed in the electrolyte. The action is similar to that heretofore given. Articles of iron, steel, zinc, tin, and lead cannot be silvered or gilded unless first covered with a thin coating of copper.

All silver plating, nickeling, gold plating, and so on, is done by this process.

461. Electrotyping consists in copying medals, wood-cuts, type, and the like in metal, usually copper, by means of the electric current. A mold of the object is taken in wax or plaster of Paris. This is evenly covered with powdered graphite to make the surface a conductor, and treated very much as an object to be plated. When the deposit has become sufficiently thick it is removed from the mold and backed or filled with type-metal.

Nearly all books nowadays are printed from electrotype plates, and not as formerly from movable types.

462. The Storage Cell. — Attach two lead plates, to which are soldered copper wires, to the opposite sides of a block of dry wood, and immerse them in dilute sulphuric acid, one part acid to five of

water (Fig. 390). Connect this cell to a suitable battery B by means of key K_1; also to an ordinary electric house bell H through a key K_2 (Fig. 391). A galvanoscope G may be included in the circuit to show the direction of the current. Pass a current through the lead cell for a few minutes by closing the key K_1. Hydrogen bubbles will be disengaged from the cathode, while the anode will begin to turn dark brown. Next open the key K_1, thus disconnecting the battery B, and close key K_2. The bell will ring and the galvanoscope will indicate a discharge current in the opposite direction to the first or charging current. The bell will soon cease ringing, and the charging may be repeated by again closing key K_1 while K_2 is open.

FIGURE 390. — SIMPLE STORAGE CELL.

The lead plates in an electrolyte of sulphuric acids illustrate a simple *lead storage cell.* The electrolysis of the sulphuric acid liberates oxygen at the anode, which combines with the lead electrode to form a chocolate-colored deposit of lead peroxide (PbO_2). Hydrogen accumulates on the cathode. When the charging battery is disconnected and the lead plates are joined by a conductor, a current flows in the external circuit from the chocolate-colored plate, which is called the *positive electrode,* to the other one, called the *negative;* the lead peroxide is reduced to spongy lead on the positive plate, while some lead sulphate is formed on the negative. During subsequent charging this lead sulphate is reduced by the hydrogen to spongy lead. Note that the charging

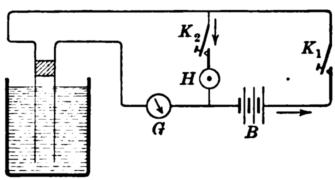


FIGURE 391. — CHARGING AND DISCHARGING STORAGE CELL.

current passes through the storage cell in the opposite direction to the discharge current furnished by the cell itself.

The storage battery stores energy and not electricity. The energy of the charging current is converted into the potential energy of chemical separation in the storage cell. When the circuit of the charged secondary cell is closed, the potential chemical energy is reconverted into the energy of an electric current in precisely the same way as in a primary cell.

FIGURE 392. — STORAGE CELL WITH THREE PLATES.

Figure 392 shows a complete storage cell containing one positive and two negative plates.

463. The Edison Storage Cell. — The positive electrode of this cell consists of hydrated nickel oxide packed in a steel grid; the negative, of finely divided iron packed in another grid. The electrolyte is a solution of caustic potash. During the discharge the iron is oxidized and the nickel oxide is reduced. These cells are lighter and stronger than lead storage cells and they may be charged more rapidly; but their E.M.F. is lower and their efficiency less.

III. OHM'S LAW AND ITS APPLICATIONS

464. Resistance. — Every conductor presents some obstruction to the passage of electricity. This obstruction is called its *electrical resistance.* The greater the conductance of a conductor the less its resistance, the one decreasing in the same ratio as the other increases. Resistance is the reciprocal of *conductance.* If R is the

resistance of a conductor and C its conductance, then $R = \frac{1}{C}$.

465. Unit of Resistance. — The primary standard unit of resistance is the *ohm.* It is represented by *the resistance of a uniform thread of mercury* 106.3 *cm. long and* 14.5421 *g. in mass, at* 0° C. This standard is reproducible because mercury can be obtained in great purity.

A commercial standard for practical purposes consists of a resistance coil of suitable wire, adjusted to be exactly equal to the primary legal mercury standard at some definite temperature.

466. Laws of Resistance. — 1. *The resistance of a conductor is proportional to its length.* For example, if 39 ft. of No. 24 copper wire (B. & S. gauge) have a resistance of 1 ohm, then 78 ft. of the same wire will have a resistance of 2 ohms.

2. *The resistance of a conductor is inversely proportional to its cross sectional area.* In the case of round wire the resistance is therefore inversely proportional to the square of the diameter. For example, No. 24 copper wire has twice the diameter of No. 30. Then 39 ft. of No. 24 has a resistance of 1 ohm, and 9.75 ft. of No. 30 (one-fourth of 39) also has a resistance of 1 ohm, both at 22° C.

3. *The resistance of a conductor of given length and cross section depends upon the material of which it is made,* that is, *upon the specific resistance*, or *resistivity* of the material. For example, the resistance of 2.2 ft. of No. 24 German silver wire is 1 ohm, while it takes 39 ft. of copper wire of the same diameter to give the same resistance.

467. Effect of Heat on Resistance. — Changes of temperature affect temporarily the resistance of metals, but all metals are not affected to the same extent. Nearly all

pure metals show an increase in resistance of about 0.4 per cent for a rise of temperature of 1° C., or 40 per cent for 100°.

When metals are cooled in liquid air, their resistance falls greatly. The experiments of Dewar and Fleming show that the decrease in resistance of all pure metals is such that at the absolute zero, – 273° C., they tend to become perfect conductors. Recently Kamerlingh Onnes has found that in liquid helium, – 269° C., tin and lead lose all appreciable resistance and become what he calls *super-conductors*. A current started by induction in a closed coil of lead wire continued almost undiminished for several hours without any electromotive force. It continued to flow as if by its inertia without encountering resistance.

The resistance temperature coefficient of alloys is smaller than that of pure metals. That of German silver is only 0.00044 for 1° C., that is, one-tenth that of the pure metals. Such alloys as manganin and constantan have practically no temperature coefficient. This property makes them very useful for resistance coils.

The resistance of carbon and of electrolytes, unlike that of metals, falls on heating. The resistance of the filament of a carbon incandescent lamp (16 candle power), which is some 400 ohms when cold, is only 220 ohms when white hot.

468. Formula for Resistance. — The above laws are conveniently expressed in the following formula for the resistance of a wire:

$$R = k\frac{l}{C.M.},$$

in which k is a constant depending on the material, l the length of the wire in feet, and $C.M.$ denotes "circular

mils." A "mil" is a thousandth of an inch, and circular mils are the square of the mils; that is, the square of the diameter of the wire in thousandths of an inch. For example, if the diameter of a wire is 0.020 in., then in mils it is 20, and the circular mils (C.M.) will be the square of 20 or 400. Now if the length of a wire conductor is expressed in feet and its cross section in circular mils, then it is easy to give to k for each kind of conductor such a value that R in the above formula will be in ohms.

The following are the values of k in ohms for several metals, at 20° C.:

Silver	9.53	Iron	61.3	German silver	181.3
Copper	10.19	Platinum	70.5	Mercury	574.0

469. Strength of Current. — The *strength* or *intensity* of a current is measured by the magnitude of the effects produced by it. Any such effect may be made the basis of a system of measurement. The quantity of an ion deposited in a second is a convenient one to use in defining unit strength of current. *The unit of current strength is the ampere.* It is defined as the current which will deposit by electrolysis, under suitable conditions, 0.001118 g. of silver per second. The ampere deposits 4.025 g. of silver in one hour. A milliampere is a thousandth of an ampere. It is to be noted that the electrolytic method measures only the quantity of electricity passing through the decomposing cell, called a *voltameter*, or a *coulometer*, in the given time.

470. Electromotive Force *is the cause of an electric flow.* It is often called *electric pressure* from its superficial analogy to water pressure. The unit of electromotive force (E.M.F.) is the *volt. A volt is the E.M.F. which will cause a current of one ampere to flow through a resistance of one ohm.* The E.M.F. of a voltaic cell depends upon the ma-

terials employed, and is entirely independent of the size and shape of the plates. The E.M.F. of a Daniell cell and of a gravity cell is about 1.1 volts; of a Leclanché and of a dry cell, 1.5 volts; of a lead storage cell, 2 volts.

The practical international standard of electromotive force is the Weston Normal Cell. The electrodes are cadmium amalgam for the negative and mercury for the positive. The electrolyte is a saturated solution of cadmium sulphate, and the depolarizer is mercurous sulphate (Fig. 393). The E.M.F. of the Weston cell in volts is given by the following equation, the temperature t being in centigrade degrees:

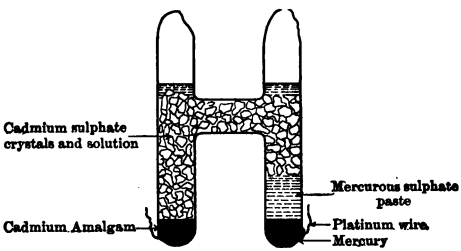


FIGURE 393.—WESTON NORMAL CELL.

$$E = 1.0183 - 0.00004\,(t - 20°). \quad \text{(Equation 35)}$$

471. Ohm's Law.—The definite relation existing between strength of current, resistance, and E.M.F. is known as *Ohm's Law:*

The strength of a current equals the electromotive force divided by the resistance; then

$$\textit{current in amperes} = \frac{\textit{E.M.F. (or potential difference) in volts}}{\textit{resistance in ohms}},$$

or in symbols,
$$I = \frac{E}{R}, \quad \ldots \ldots \quad \text{(Equation 36)}$$

where I is the current in amperes, E the E.M.F. in volts, and R the resistance in ohms. Applied to a battery, if

Alessandro Volta (1745–1827) was born at Como, Italy. He was professor of physics at the University of Pavia, and was noted for his researches and investigations in electricity. The voltaic cell, the electroscope, the electrical condenser, and the electrophorus are due to his genius.

Georg Simon Ohm (1789–1854) was born in Erlangen, Bavaria, and was educated at the University of that town. He began his investigations by measuring the electrical conductivity of metals. In 1827 he announced the electrical law named in his honor, and in 1842 he was elected to a professorship in the University of Munich

r is the resistance external to the cell, and r' the internal resistance of the cell itself, then

$$I = \frac{E}{r + r'}. \quad . \quad . \quad . \quad . \quad \text{(Equation 37)}$$

From Equation 36, $E = IR$ and $R = \frac{E}{I}$.

472. Methods of Varying Strength of Current. — It is evident from Ohm's law that the strength of the current furnished by an electric generator may be increased in two ways: (1) by increasing the E.M.F.; (2) by reducing the internal resistance.

The E.M.F. may be increased by joining several cells *in series*, and the internal resistance may be diminished by connecting them *in parallel*. Enlarging the plates of a battery or bringing them closer together diminishes the internal resistance.

FIGURE 394. — CELLS CONNECTED IN SERIES.

473. Connecting in Series. — To connect cells in series, join the positive electrode of one to the negative electrode of the next, and so on until all are connected. The electrodes of the *battery* thus connected in series are the positive electrode of the last one in the series and the negative electrode of the first one (Fig. 394). Figure 395 is the conventional sign for a single cell; Figure 396 shows four cells in series.

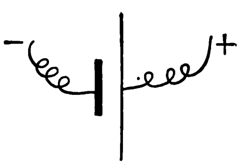
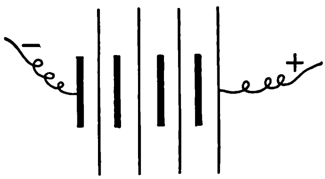


FIGURE 395. — SIGN FOR SINGLE CELL.

When n similar cells are connected in series, the E.M.F. of the battery is

n times that of a single cell; the resistance is also n times the resistance of one cell. Hence, by Ohm's law for n cells connected in series the current is

$$I = \frac{nE}{r + nr'}.$$



Figupe 396.—Four Cells in Series.

To illustrate, if four cells, each having E.M.F. of 2 volts and an internal resistance of 0.5 ohm, are joined in series with an external resistance of 10 ohms, the current will be

$$I = \frac{4 \times 2}{10 + 4 \times 0.5} = 0.67 \text{ ampere.}$$

474. Connecting in Parallel. — When all the positive terminals are connected together on one side and the negative on the other, the cells are grouped in *parallel* (Fig. 397). With n similar cells the effect of such a grouping is to reduce the internal resistance to $\frac{1}{n}$th that of a single cell. It is equivalent to increasing the area of the plates n times. All the cells side by side contribute equal shares to the output of the battery. The E.M.F. of the group is the same as that of a single cell.

Figure 397.—Cells in Parallel.

Connection in parallel is used chiefly with storage cells, not for the purpose of reducing the internal resistance of the battery, but for the purpose of permitting a larger current to be drawn from it with safety to the cells. The ampere capacity of a storage cell depends on the area of the plates. If twenty amperes may be drawn from a single storage cell, then from two such cells in parallel forty amperes may be taken.

IV. HEATING EFFECTS OF A CURRENT

475. Electric Energy Converted into Heat. — Send an electric current through a piece of fine iron wire. The wire is heated, and it may be fused if the current is sufficiently strong.

The conversion of electrical energy into other forms is a familiar fact. In the storage battery the energy of the charging current is converted into the energy of chemical separation and stored as the potential energy of the charged cells. In this experiment the energy of the current is transformed into heat because of the resistance which the wire offers. If the resistance of an electric circuit is not uniform, the most heat will be generated where the resistance is the greatest.

Send the current from a few cells through a chain made of alternate pieces of iron and copper, soldered together (Fig. 398). The iron links may be made to glow red hot, while the copper ones remain comparatively cool. The resistance of the iron wire is about seven times as great as that of copper of the same length and gauge. Moreover, its thermal capacity is about three-quarters as great. Hence the rise of temperature of the iron links is roughly nine times as great as that of the copper ones.

FIGURE 398. — IRON AND COPPER LINKS.

476. Joule's Law. — Joule demonstrated experimentally that the number of units of heat generated in a conductor by an electric current is proportional:

a. To the resistance of the conductor.
b. To the square of the strength of current.
c. To the length of time the current flows.[1]

[1] If H is the heat in calories, I the current strength in amperes, R the resistance in ohms, t the time in seconds, and 0.24 the number of calories equivalent to one joule, then the heat equivalent of a current is

$$H = 0.24 \times I^2Rt \text{ calories.}$$

477. Applications of Electric Heating. — Some of the more important applications of electric heating are the following:

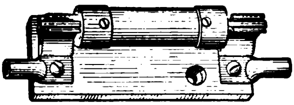


FIGURE 399. — CARTRIDGE FUSE.

1. *Electric Cautery.* A thin platinum wire heated to incandescence is employed in surgery instead of a knife. Platinum is very infusible and is not corrosive.

2. *Safety Fuses.* Advantage is taken of the low temperature of fusion of some alloys, in which lead is a constituent, for making safety fuses to open a circuit automatically whenever the current becomes excessive (Fig. 399).

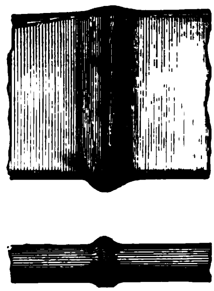


FIGURE 400. — ELECTRICALLY WELDED JOINTS.

3. *Electric Welding.* If the abutting ends of two rods or bars are pressed together, while a large current passes through them, enough heat is generated at the junction, where the resistance is greatest, to soften and weld them together. Figure 400 shows two welded joints as they came from the welder.

4. *The Electric Flatiron.* Figure 401 shows a flatiron, partly cut away, arranged to be heated by an electric current. The current enters by a flexible conductor and flows through the resistance coil E on the base of the iron. A is a wooden handle to avoid the use of a holder. The resistance is often arranged so as to concentrate the heat at the point of iron.

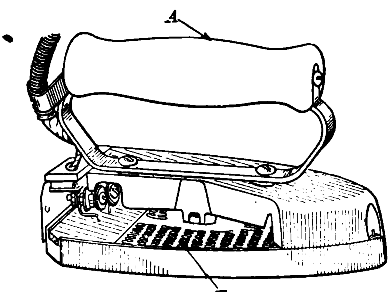


FIGURE 401. — ELECTRIC FLATIRON.

5. *Electric Heating.* Electric street cars are often heated by a current through suitable resistances. Similar devices for cooking are now articles of commerce. Small furnaces for fusing, vulcanizing, and enameling are common in dentistry.

Large furnaces are employed for melting refractory substances, for the reduction of certain ores, and for chemical operations demanding a high temperature.

V. MAGNETIC PROPERTIES OF A CURRENT

478. Magnetic Field Around a Conductor. — Dip a portion of a wire carrying a heavy current into fine iron filings. A thick cluster of them will adhere to the wire (Fig. 402); they will drop off as soon as the circuit is opened.

FIGURE 402. — MAGNETIC FIELD AROUND A CURRENT.

The experiment shows that a conductor through which an electric current is passing has magnetic properties. The iron filings are magnetized by the current and set themselves at right angles to the wire. When the circuit is broken, they lose their magnetism and drop off.

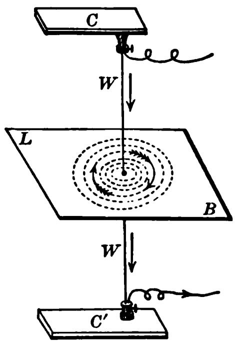


FIGURE 403. — MAPPING MAGNETIC FIELD.

479. Mapping the Magnetic Field. — Support horizontally a sheet of cardboard or of glass *LB* with a hole through it. Pass vertically through the hole a wire, *W*, connecting with a suitable electric generator, so that a strong current can be sent through the circuit (Fig. 403). Close the circuit and sift iron filings on the paper or glass about the wire, jarring the sheet by tapping it. The filings will arrange themselves in circular lines about the wire. Place a small mounted magnetic needle on the sheet near the wire; it will set itself tangent to the circular lines, and if the current is flowing downward, the north pole will point in the direction in which the hands of a watch move.

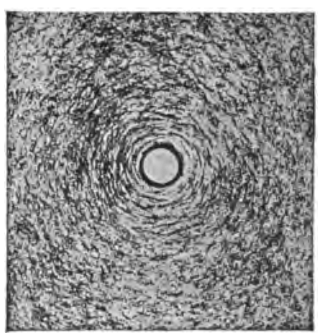


FIGURE 404. — CIRCULAR LINES OF FORCE AROUND A WIRE.

The lines of magnetic force about a wire through which an electric current is flowing, are concentric circles. Figure 404

was made from a photograph of these circular lines of force as shown by iron filings on a plate of glass. Their direction relative to the current is given by the following rule:

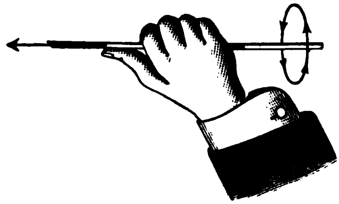


FIGURE 405. — FINGERS SHOW DIRECTION OF LINES OF FORCE.

Grasp the wire by the right hand so that the extended thumb points in the direction of the current; then the fingers wrapped around the wire indicate the direction of the lines of force (Fig. 405).

Figure 406 is a sketch intended to show the direction of

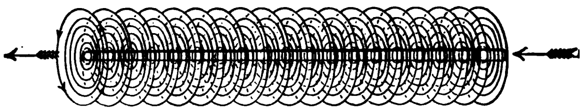


FIGURE 406. — MAGNETIC WHIRL.

these circular lines of magnetic force (or magnetic whirl) which everywhere surround a wire conveying a current.

480. Properties of a Circular Conductor. — Bend a copper wire into the form shown in Figure 407, the diameter of the circle being about 20 cm. Suspend it by a long untwisted thread, so that the ends dip into the mercury cups shown in cross section in the lower part of the figure. Send a current through the suspended wire by connecting a battery to the binding posts. A bar magnet brought near the face of the circular conductor will cause the latter to turn about a vertical axis and take up a position with its plane at right angles to the axis of the magnet. With a strong current the circle will turn under the influence of the earth's magnetism.

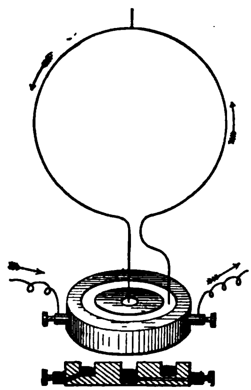


FIGURE 407. — DEFLECTION OF CIRCULAR CURRENT BY A MAGNET.

This experiment shows that a circular current acts like a disk magnet, whose poles are its faces. The lines of force surrounding the conductor in this form pass through the circle and around from one face to the other through the air outside the loop. The north-seeking side is the one from which the lines issue; and to an observer looking toward the side, the current flows around the loop counterclockwise (Fig. 408).

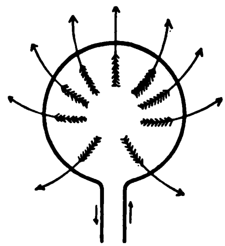


FIGURE 408. — LINES OF FORCE THROUGH A LOOP.

If instead of a single turn we take a long insulated wire and coil it into a number of parallel circles close together, the magnetic effect will be increased. Such a coil is called a *helix* or *solenoid;* and the passage of an electric current through it gives to it all the properties of a cylindrical bar magnet.

Thread a loose coil of copper wire through holes in a sheet of mica, so that each turn lies half on one side and half on the other (Fig. 409). Place horizontally and scatter fine iron filings evenly over the mica. Send a strong current through the coil and gently tap the mica. The filings will gather in the general direction of the lines of force through the helix.

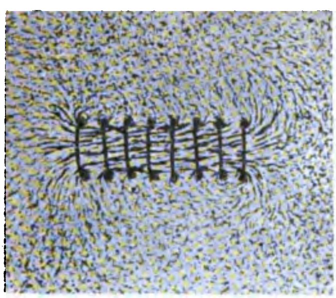


FIGURE 409. — FIELD IN HELIX.

481. Polarity of a Helix. — The polarity of a helix may be determined by the following rule:

Grasp the coil with the right hand so that the fingers point in the direction of the current; the north pole will then be in the direction of the extended thumb.

482. Mutual Action of Two Currents. — Make a rectangular coil of insulated copper wire by winding four or five layers around the edge of a board about 25 cm. square. Slip the wire off the board and tie the parts together in a number of places with thread. Bend the ends at right angles to the frame, remove the insulation, and give them the shape shown in Figure 410. Suspend the wire frame by a long thread so that the ends dip into the mercury cups.

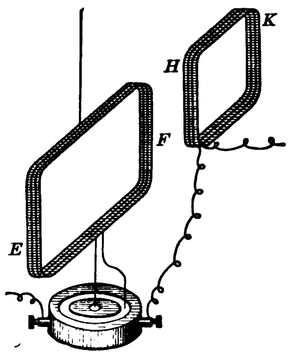


FIGURE 410. — ACTION BETWEEN TWO CIRCUITS.

Make a second similar but smaller coil and connect it in the same circuit with the rectangular coil and a battery.

First. Hold the coil HK with its plane perpendicular to the plane of the coil EF, with its edge H parallel to F, and with the currents in these two adjacent portions flowing in the same direction. The suspended coil will turn upon its axis, the edge F approaching H, as if it were attracted.

Second. Reverse HK so that the currents in the adjacent portions K and F flow in opposite directions. The edge F of the suspended coil will be repelled by K.

Third. Hold the coil HK within EF, so that their lower sides form an angle. EF will turn until the currents in its lower side are parallel with those in H, and flowing in the same direction.

Mount a long flexible helix as in Figure 411, with the free end just dipping into the mercury in the glass cup. Pass a sufficient current through it; it will shorten because of the attraction between parallel turns, until the lower end leaves the mercury and breaks the circuit. It will then lengthen and close the circuit ready for another oscillation.

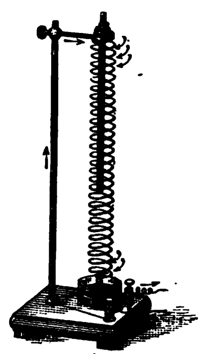


FIGURE 411. — ATTRACTION BETWEEN TURNS.

These facts may be summarized in the following *laws of action between currents:*

I. *Parallel currents flowing in the same direction attract.*

II. *Parallel currents flowing in opposite directions repel.*

III. *Currents making an angle with each other tend to become parallel and to flow in the same direction.*

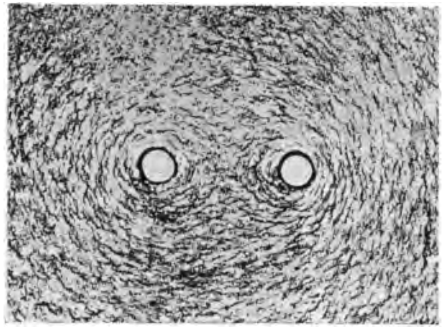


FIGURE 412. — MAGNETIC FIELD ABOUT PARALLEL CURRENTS IN THE SAME DIRECTION.

483. Magnetic Fields about Parallel Currents. — Figure 412 was made from a photograph of the magnetic field about two parallel currents in the same direction perpendicular to the figure. Many of these lines of force surround both wires, and it is the tension along them that draws the wires together. Figure 413 was made from a photograph of the field when the currents were in opposite directions. The lines of force are crowded together between the wires, and their reaction in their effort to recover their normal position forces the wires apart.

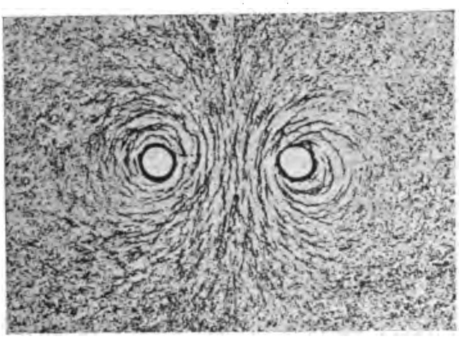


FIGURE 413. — MAGNETIC FIELD ABOUT PARALLEL CURRENTS IN OPPOSITE DIRECTIONS.

VI. ELECTROMAGNETS

484. Effect of Introducing Iron into a Solenoid. — Fill the lower half of the helix of § 480 with soft straight iron wires, and again pass the same current as before through the coil. The magnetic field will be greatly strengthened by the iron.

A helix of wire about an iron core is an *electromagnet.* It was first made by Sturgeon in 1825. The presence of the iron core greatly increases the number of lines of force threading through the helix from end to end, by reason of

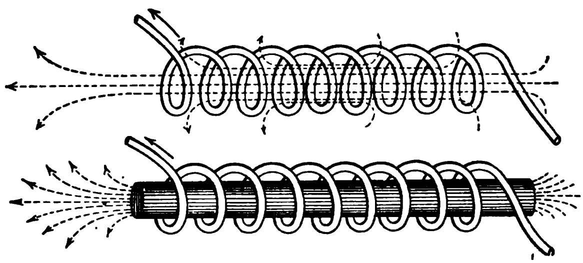


FIGURE 414. — IRON INCREASES MAGNETIC LINES.

the greater permeability of iron as compared with air (Fig. 414). If the iron is omitted, there are not only fewer lines of force, but because of their leakage at the sides of the helix, fewer traverse the entire length of the coil.

The soft iron core of an electromagnet does not show much magnetism except while the current is flowing through the magnetizing coil. The loss of magnetism is not quite complete when the current is interrupted; the small amount remaining is called *residual magnetism.*

485. Relation between a Magnet and a Flexible Conductor. — Iron filings arranged in circles about a conductor may be regarded as flexible magnetized iron winding itself into a helix around the current; conversely, a flexible conductor, carrying a current, winds

James Clerk-Maxwell (1831–1879) was a remarkable physicist and mathematician. He was born in Edinburgh and studied in the University of that city. Later he attended the University of Cambridge, graduating from there in 1854. In 1856 he became professor of natural philosophy at Marischal College, Aberdeen, and in 1860 professor of physics and astronomy at King's College, London. In 1871 he was appointed professor of experimental physics in Cambridge. His contributions to the kinetic theory of gases, the theory of heat, dynamics, and the mathematical theory of electricity and magnetism are imperishable monuments to his great genius and wonderful insight into the mysteries of nature.

itself around a straight bar magnet. The flexible conductor of Figure 415 may be made of tinsel cord or braid. Directly the circuit is closed, the conductor winds slowly around the vertical magnet; if the current is then reversed, the conductor unwinds and winds up again in the reverse direction.

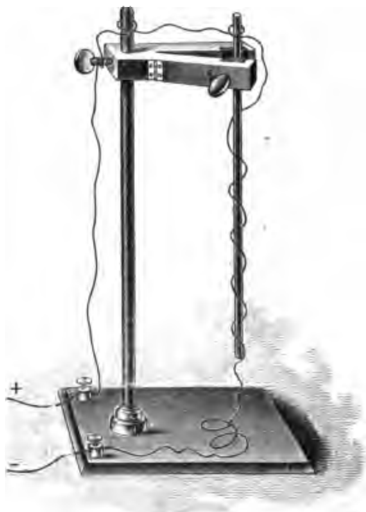


FIGURE 415. — FLEXIBLE CONDUCTOR WINDS ITSELF AROUND A MAGNET.

486. The Horseshoe Magnet. — The form given to an electromagnet depends on the use to which it is to be put. The *horseshoe* or U-shape (Fig. 416) is the most common. The advantage of this form lies in the fact that all lines of magnetic force are closed curves, passing through the core from the south to the north pole, and completing the circuit through the air from the north pole back to the south pole. The U-shape lessens the distance through the air and thus increases the number of lines. Moreover, when an iron bar, called the *armature*, is placed across the poles, the air gap is reduced to a thin film, the number of lines is increased to a maximum with a given current through the helix, and the magnet exercises the greatest pull on the armature.

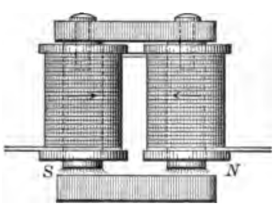


FIGURE 416. — HORSESHOE MAGNET.

When the armature is in contact with the poles, the magnetic circuit is all iron, and is said to be a *closed*

magnetic circuit. The residual magnetism is then much greater than in the case of an open magnetic circuit with an air gap.

Bring the armature in contact with the iron poles of the core, and close the electric circuit; after the circuit is opened, the armature will still cling to the poles and can be removed only with some effort. Then place a piece of thin paper between the poles and the armature. After the magnet has again been excited and the circuit opened, the armature will not now "stick." The paper makes a thin air gap between the poles of the magnet and the armature, and thus reduces the residual magnetism.

FIGURE 417. — LIFTING MAGNET.

487. Applications of Electromagnets.— The uses to which electromagnets are put in the applications of electricity are so numerous that a mere reference to them must suffice. The electromagnet enters into the construction of electric bells, telegraph and telephone instruments, dynamos, motors, signaling devices, etc. It is also extensively used in lifting large masses of iron, such as castings, rolled plates, pig iron, and steel girders (Fig. 417). The lifting power depends chiefly on the cross section of the iron core and on the *ampere turns;* that is, on the product of the number of amperes of current and the number of turns of wire wound on the magnet.

VII. MEASURING INSTRUMENTS

488. The Galvanometer. — The instrument for the comparison of currents by means of their magnetic effects is called a *galvanometer.* A galvanoscope (§ 446) becomes a galvanometer by providing it with a scale so that the deflections may be measured. If the galvanometer is calibrated, so as to read directly in amperes, it is called an *ammeter.* In very sensitive instruments a small mirror is

attached to the movable part of the instrument; it is then called a *mirror galvanometer*. Sometimes a beam of light from a lamp is reflected from this small mirror back to a scale, and sometimes the light from a scale is reflected back to a small telescope, by means of which the deflections are read. In either case the beam of light then becomes a long pointer without weight.

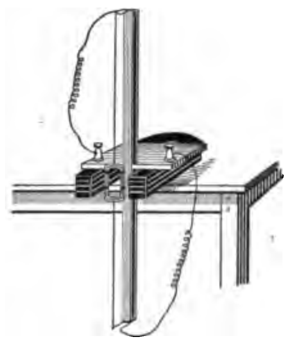


FIGURE 418. — PLAN OF D'ARSONVAL GALVANOMETER.

489. The d'Arsonval Galvanometer. — One of the most useful forms of galvanometer is the d'Arsonval. The plan of it is shown in Figure 418 and a complete working instrument in Figure 419. Between the poles of a strong permanent magnet of the horseshoe form swings a rectangular coil of fine wire in such a way that the current is led into the coil by the fine suspending wire, and out by the wire spiral running to the base. A small mirror is attached to the coil to reflect light from a lamp or an illuminated scale. Sometimes the coil carries a light aluminum pointer, which traverses a scale. Inside the coil is a soft iron tube supported from the back of the case. It is designed to concentrate the lines of force in the narrow openings between it and the poles of the magnet.

FIGURE 419. — SIMPLE D'ARSONVAL GALVANOMETER.

In the d'Arsonval galvanometer the coil is movable and the magnet is fixed. Its chief advantages are simplicity

of construction, comparative independence of the earth's magnetic field, and the quickness with which the coil comes to rest after deflection by a current through it.

FIGURE 420. — VOLTMETER.

490. The Voltmeter. — The *voltmeter* is an instrument designed to measure the difference of potential in volts. For direct currents the most convenient portable voltmeter is made on the principle of the d'Arsonval galvanometer. One of the best-known instruments of this class is shown in Figure 420. The interior is represented by Figure 421, where a portion of the instrument is cut away to show the coil and the springs. The current is led in by one spiral spring and out by the other. Attached to the coil is a very light aluminum pointer, which moves over the scale seen in Figure 420 where it stands at zero. Soft iron pole pieces are screwed fast to the poles of the permanent magnet, and they are so shaped that the divisions of the scale in volts are equal.

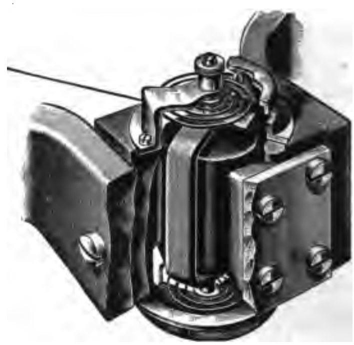


FIGURE 421. — INSIDE OF VOLTMETER.

In circuit with the coil of the instrument is a coil of wire of high resistance, so that when the voltmeter is placed in circuit, only a small current will flow through it.

491. The Ammeter, designed to measure electric currents in amperes, is very similar in construction to the voltmeter. A low resistance shunt is connected across the terminals of the coil to carry the main current, so that when the ammeter is placed in circuit, it will not change the value of the current to be measured.

Questions

1. Why must the article to be electroplated be attached to the negative pole of the generator?

2. How can you determine the positive pole of a storage battery?

3. Why will it ruin a pocket ammeter to connect its terminals to the poles of a storage battery?

4. Why does the heating in an electric circuit manifest itself at a point where the conductor is defective?

5. If in Figure 415 the north pole of the magnet is at the top, which way will the flexible tinsel wrap around the magnet?

6. Why should the ammeter be of low resistance and the voltmeter of high resistance?

7. Why should a Daniell cell when not in use either be taken down or placed on closed circuit?

8. Why must the wire used in winding an electromagnet be insulated?

9. What is the least number of gravity cells that might be used to charge a storage battery and how must they be connected?

10. What would be the harm of leaving a dry cell on a closed circuit?

11. Why will a low resistance voltmeter give the E.M.F. of a storage battery more nearly correct than it will that of a dry cell?

12. Why will cotton-wound wire be sufficiently insulated for a battery, but not for a Holtz machine?

492. Divided Circuits — Shunts. — When the wire leading from any electric generator is divided into two branches, as at *B* (Fig. 422), the current also divides, part flowing

by one path and part by the other. The sum of these two currents is always equal to the current in the undivided part of the circuit, since there is no accumulation of electricity at any point. Either of the branches between B and A is called a *shunt* to the other, and *the currents through them are inversely proportional to their resistances.*

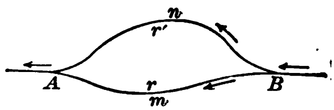


FIGURE 422. — DIVIDED CIRCUIT.

493. Resistance of a Divided Circuit. — Let the total resistance between the points A and B (Fig. 422) be represented by R, that of the branch BmA by r, and of BnA by r'. The conductance of BA equals the sum of the conductances of the two branches; and, as conductance is the reciprocal of resistance, the conductances of BA, BmA, and BnA are $\frac{1}{R}$, $\frac{1}{r}$, and $\frac{1}{r'}$ respectively; then $\frac{1}{R} = \frac{1}{r} + \frac{1}{r'}$. From this we derive $R = \frac{rr'}{r + r'}$. To illustrate, let a galvanometer whose resistance is 100 ohms have its binding posts connected by a shunt of 50 ohms resistance; then the total resistance of this divided circuit is $\frac{100 \times 50}{100 + 50} = 33\frac{1}{3}$ ohms. The introduction of a shunt always lessens the resistance between the points connected.

494. Loss of Potential along a Conductor. — Stretch a fine wire of fairly high resistance, such as a German silver No. 30, along the edge of a meter stick (Fig. 423). Connect the ends P and Q to a storage cell with a contact key in circuit. At P connect a galvanometer in circuit with a high resistance R and a slide contact S. The galvanometer will indicate the difference of potential between P and S, the point of contact on PQ. If S be placed successively on PQ at 10 cm., 20 cm., 30 cm., etc., from P, and

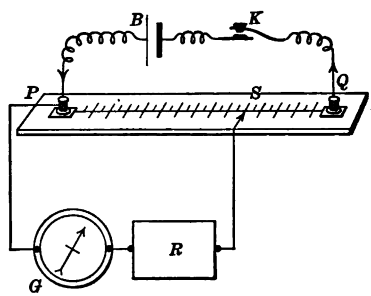


FIGURE 423. — FALL OF POTENTIAL ALONG A CONDUCTOR.

the galvanometer reading be recorded each time, the ratio of the readings will be as 1 : 2 : 3, etc. Since resistance is proportional to length, these potential differences are as the resistances of the successive lengths of the wire PQ, or *the loss of potential is proportional to the resistance passed over.*

This is equivalent to another statement of Ohm's law; for since $I = \frac{E}{R}$, and the current through the conductor is the same at all points, it follows that E must vary as R to make I constant.

495. Wheatstone's Bridge. — The Wheatstone's Bridge is a device for measuring resistances. The four conductors, R_1, R_2, R_3, R_4 are the *arms* and BD the *bridge* (Fig. 424). When the circuit is closed by closing the key K_2, the current divides at A, the two parts reuniting at C. The loss of potential along ABC is the same as along ADC. If no current flows through the galvanometer G when the key K_1 is also closed, then there is no potential difference between B and D to produce a current. Under these conditions the loss of potential from A to B is the same as from A to D. We may then get an expression for these potential differences and place them equal to each other.

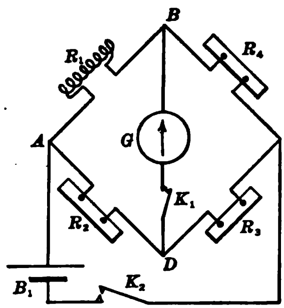


FIGURE 424. — WHEATSTONE'S BRIDGE.

Let I_1 be the current through R_1; it will also be the current through R_4, because none flows across through the galvanometer. Also let I_2 be the current through the branch ADC. Then the potential difference between A and B by Ohm's law (§ 471) is equal to R_1I_1; and the equal potential difference between A and D is R_2I_2. Equating these expressions,

$$R_1I_1 = R_2I_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

In the same way the equal potential differences between B and C and D and C give

$$R_4I_1 = R_3I_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

Dividing (*a*) by (*b*) gives

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(Equation 38)}$$

In practice three of the four resistances are adjustable and of known value. They are adjusted until the galvanometer shows no deflection when the key K_1 is closed after key K_2. The value of the fourth resistance is then derived from the relation in Equation 38.

Problems

1. Calculate the resistance of 200 ft. of copper wire ($k = 10.19$) No. 24 (diameter = 0.0201 in.).

2. A coil of iron wire ($k = 61.3$) is to have a resistance of 25 ohms. The diameter of the wire used is 0.032 in. How many feet will it require?

3. What diameter must a copper trolley ($k = 10.19$) have so that the resistance will be half an ohm to the mile?

4. A current of one ampere deposits by electrolysis 1.1833 g. of copper in an hour. How long will it take a current of 5 amperes to deposit a kilogram of copper?

5. A current of two amperes passes through a solution of silver nitrate for one hour. How much silver will be deposited?

6. A current of 10 amperes is sent through a resistance of 4 ohms for 10 minutes. How many calories of heat are generated?

7. What current will 6 dry cells connected in series, each having an E. M. F. of 1.5 volts and an internal resistance of 0.1 ohm, give through an external resistance of 2 ohms?

8. A certain dry cell has a voltage of 1.5 volts and when tested with an ammeter gives 20 amperes. What is its internal resistance?

9. A certain lamp requires 0.5 ampere current and an E. M. F. of 110 volts to light it. What is its resistance?

10. A projection lantern requires a current of 15 amperes. The voltage of the supply is 110 volts and the loss in the lamp is 40 volts. What resistance must be inserted in the line to the lantern?

Michael Faraday, 1791–1867, was born near London, England. He was the son of a blacksmith and received but little schooling, being apprenticed to a bookbinder when only thirteen years of age. While employed in the bindery he became interested in reading such scientific books as he found there. Later he applied to Sir Humphry Davy for consideration and was made Davy's assistant. From this time his rise was rapid; in 1816 he published his first scientific memoir; in 1824 he became a member of the Royal Society; in 1825 he was elected director of the Royal Institution; in 1831 he announced the discovery of magneto-electric induction, the most important scientific discovery of any age. In 1833 he was elected professor of chemistry in the Royal Institution. He was a remarkable experimenter and a most interesting lecturer, and amid all his wonderful achievements, he was utterly wanting in vanity.

CHAPTER XIII

ELECTROMAGNETIC INDUCTION

I. FARADAY'S DISCOVERIES

496. Electromotive Force Induced by a Magnet. — Wind a large number of turns of fine insulated wire around the armature of a horseshoe magnet, leaving the ends of the iron free to come in contact with the poles of the permanent magnet. Connect the ends of the coil to a sensitive galvanometer, the armature being in contact with the magnetic poles, as shown in Figure 425. Keeping the magnet fixed, suddenly pull off the armature. The galvanometer will show a momentary current. Suddenly bring the armature up against the poles of the magnet; another momentary current in the reverse direction will flow through the circuit. This experiment illustrates Faraday's original method of producing an electric current through the agency of magnetism.

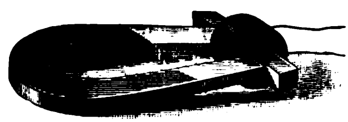


FIGURE 425. — FARADAY'S ORIGINAL EXPERIMENT ON INDUCED E. M. F.

Connect a coil of insulated copper wire, at least fifty turns of No. 24, in circuit with a d'Arsonval galvanometer (Fig. 426). Thrust quickly into the coil the north pole of a bar magnet. The galvanometer will show a transient current, which will flow only during the motion of the magnet. When the magnet is suddenly withdrawn

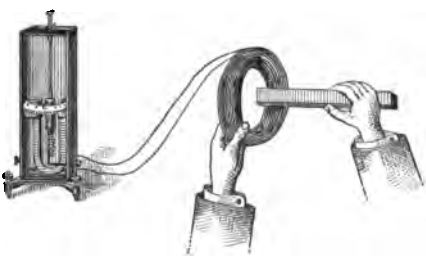


FIGURE 426. — CURRENT INDUCED BY THRUSTING MAGNET INTO COIL.

a transient current is produced in the opposite direction to the first one. If the south pole be thrust into the coil, and then withdrawn, the currents in both cases are the reverse of those with the north pole. If we substitute a helix of a smaller number of turns, or a weaker bar magnet, the deflection will be less.

The momentary electromotive forces generated in the coil are known as *induced electromotive forces*, and the currents as *induced currents*. They were discovered by Faraday in 1831.

497. Laws of Electromagnetic Induction. — When the armature in the first experiment of the last article is in contact with the poles of the magnet, the number of lines of force passing through the coil, or linked with it, is a maximum. When the armature is pulled away, the number of magnetic lines threading through the coil rapidly diminishes.

When the magnet in the second experiment is thrust into the coil, it carries its lines of force with it, so that some of them at least encircle, or are linked with, the wires of the coil. In both experiments an electromotive force is generated only while the number of lines so linked with the coil is changing. The E.M.F. is generated in the coil in accordance with the following laws:

I. *An increase in the number of lines of force linked with a conducting circuit produces an indirect E.M.F.; a decrease in the number of lines produces a direct E.M.F.*

II. *The induced E.M.F. at any instant is equal to the rate of increase or decrease in the number of lines of force linked with the circuit.*

A *direct* E.M.F. has a *clockwise* direction to an observer looking along the lines of force of the magnet; an *indirect* E.M.F. is one in the opposite direction. Thus, in Figure

427 the north pole of the magnet is moving into the coil in the direction of the arrow; there is an *increase* in the number of lines passing through the coil, and the E. M.F. and current are *indirect* or opposite watch hands, as shown by the arrows on the coil, to an observer looking at the coil in the direction of the arrow on the magnet.

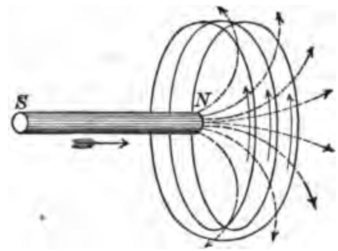


FIGURE 427. — DIRECTION OF INDUCED E.M.F.

498. Induction by Currents. — Connect the *S* coil of Figure 428 to a d'Arsonval galvanometer, and a second smaller coil *P* to the terminals of a battery. If the current through *P* is kept constant, when *P* is made to approach *S* an E. M. F. is generated in *S* tending to send a current in a direction opposite to the current around *P*; removing the coil *P* generates an opposite E. M. F. These E. M. F.'s act in *S* only so long as *P* is moving.

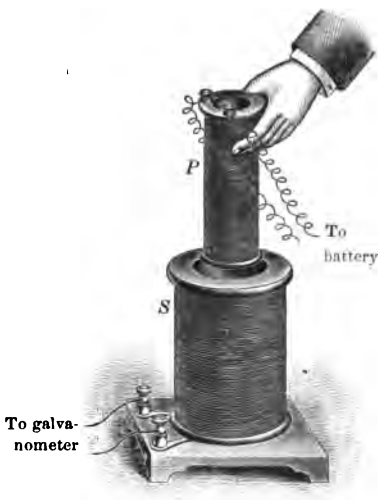


FIGURE 428. — CURRENTS INDUCED BY ANOTHER CURRENT.

Next insert the coil *P* in *S* with the battery circuit open. If then the battery circuit is closed, the needle of the galvanometer will be deflected, but will shortly come again to rest at zero. The direction of this momentary current is opposite to that in *P*. Opening the battery circuit produces another momentary current through *S* but in the opposite direction. Increasing and decreasing the current through *P* has the same effect as closing and opening the circuit.

If while P is inside S with the battery circuit closed, a bar of soft iron is placed within P, there is an increase of magnetic lines through both coils and the inductive effect in S is the same as that produced by closing the circuit through P.

The coil P is called the *primary* and S the *secondary* coil. The results may be summarized as follows:

I. *A momentary current in the opposite direction is induced in the secondary conductor by the approach, the starting, or the strengthening of a current in the primary.*

II. *A momentary current in the same direction is induced in the secondary by the receding, the stopping, or the weakening of the current in the primary.*

The primary coil becomes a magnet when carrying an electric current (§ 480) and acts toward the secondary coil as if it were a magnet. The soft iron increases the magnetic flux through the coil and so increases the induction.

499. Lenz's Law. — When the north pole of the magnet is thrust into the coil of Figure 427, the induced current flowing in the direction of the arrows produces lines of force running in the opposite direction to those from the magnet (§ 479). These lines of force tend to oppose the change in the magnetic field within the coil, or the magnetic field set up by the coil opposes the motion of the magnet.

Again, when the primary coil of Figure 428 is inserted into the secondary, the induced current in the latter is opposite in direction to the primary current, and parallel currents in opposite directions repel each other. In every case of electromagnetic induction the change in the magnetic field which produces the induced current is always opposed by the magnetic field due to the induced current itself.

Joseph Henry (1797–1878) was born at Albany, New York. The reading of Gregory's Lectures on Experimental Philosophy interested him so greatly in science that he began experimenting. In 1829 he constructed his first electromagnet. In 1832 he was appointed professor of natural philosophy at Princeton College. In 1846 he became secretary of the Smithsonian Institution in Washington. It is almost certain that he anticipated Faraday's great discovery of magneto-electric induction by a whole year but failed to announce it. His principal investigations were in electricity and magnetism, and chiefly in the realm of induced currents.

The law of Lenz respecting the direction of the induced current is broadly as follows:

The direction of an induced current is always such that it produces a magnetic field opposing the motion or change which induces the current.

II. SELF-INDUCTION

500. Joseph Henry's Discovery. — Joseph Henry discovered that a current through a helix with parallel turns acts inductively on its own circuit, producing what is often called the *extra current*, and a bright spark across the gap when the circuit is opened. The effects are not very marked unless the helix contains a soft iron core.

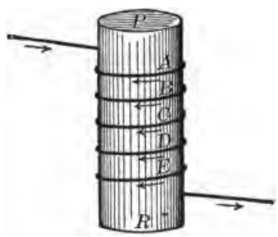


FIGURE 429. — SELF-INDUCTION.

Let a coil of wire be wound around a wooden cylinder (Fig. 429). When a current is flowing through this coil, some of the lines of force around one turn, as *A*, thread through adjacent turns; if the cylinder is iron, the number of lines threading through adjacent turns will be largely increased on account of the superior permeability of the iron (§ 401). Hence, at the make of the circuit, the production of magnetic lines threading through the parallel turns of wire induces a counter-E.M.F. opposing the current. The result is that the current does not reach at once the value given by Ohm's law. At the break of the circuit, the induction on the other hand produces a direct E.M.F. tending to prolong the current. With many turns of wire, this direct E.M.F. is high enough to break over a short gap and produce a spark.

501. Illustrations of Self-Induction. — Connect two or three cells in series. Join electrically a flat file to one pole and a piece of iron wire to the other. Draw the end of the wire lengthwise along the file; some sparks will be visible, but they emit little light. Now put an electromagnet in the circuit to increase the self-induction; the sparks are now much longer and brighter.

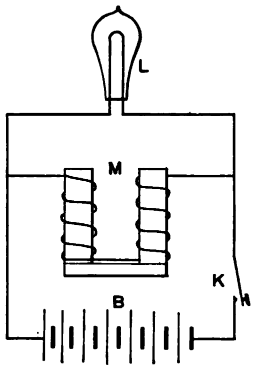


FIGURE 430. — LAMP LIGHTED BY SELF-INDUCTION OF MAGNET.

Connect as shown in Figure 430 a large electromagnet *M*, a storage battery *B*, a circuit breaker *K*, and an incandescent lamp *L* of such a size that the battery alone will light it to nearly its full candle power. The circuit divides between the lamp and the electromagnet, and since the latter is of low resistance, when the current reaches its steady state most of it will go through the coils of the magnet, leaving the lamp at only a dull red. At the instant when the circuit is closed, the self-induction of the magnet acts against the current and sends most of it around through the lamp. It accordingly lights up at first, but quickly grows dim as the current rises to its steady value in *M*.

Now open the circuit breaker *K*, cutting off the battery. The only closed circuit is now the one through the magnet and the lamp; but the energy stored in the magnetic field of the electromagnet is then converted into electric energy by means of self-induction, and the lamp again lights up brightly for a moment.

III. THE INDUCTION COIL

502. Structure of an Induction Coil. — The *induction coil* is commonly used to give transient flashes of high electromotive force in rapid succession. A primary coil of comparatively few turns of stout wire is wound around an iron core, consisting of a bundle of iron wires to avoid induced or eddy currents in the metal of the core; outside

of this, and carefully insulated from it, is the secondary of a very large number of turns of fine wire. The inner or primary coil is connected to a battery through a circuit breaker (Fig. 431). This is an automatic device for opening and closing the primary circuit and is actuated by the magnetism of the iron core. At the "make" and "break" of the primary circuit electromotive forces are induced in the secondary in accordance with the laws of electromagnetic induction (§ 497). Large induction coils include also a *condenser*. It is placed in the base and consists of two sets of interlaid layers of tin-foil, separated by sheets of paper saturated with paraffin. The two sets are connected to two points of the primary circuit on opposite sides of the circuit breaker (Fig. 432).

FIGURE 431. — INDUCTION COIL.

503. Action of the Coil. — Figure 432 shows the arrangement of the various parts of an induction coil. The current first passes through the heavy primary wire *PP*, thence through the spring *h*, which carries the soft iron block *F*, then across to the screw *b*, and so back to the negative pole of the battery. This current magnetizes the iron core of the coil, and the core attracts the soft iron block *F*, thus breaking the circuit at the point of the screw *b*. The core is then demagnetized, and the release of *F* again closes the circuit. Electromotive forces are thus induced in the secondary coil *SS*, both at the make and the break of the primary. The high E.M.F. of the secondary is due to the large number of turns of wire in

it and to the influence of the iron core in increasing the number of lines of force which pass through the entire coil.

The self-induction of the primary has a very important bearing on the action of the coil. At the instant the circuit is closed, the counter E.M.F. opposes the battery

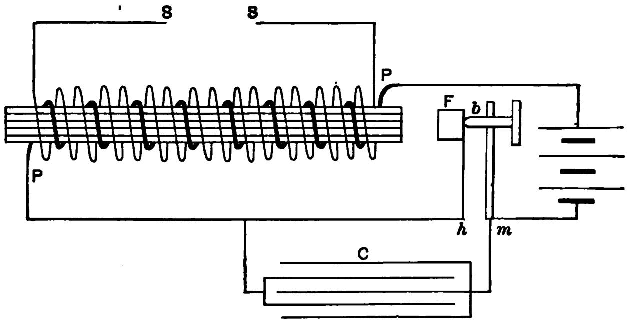


FIGURE 432. — STRUCTURE OF INDUCTION COIL.

current, and prolongs the time of reaching its greatest strength. Consequently the E.M.F. of the secondary coil will be diminished by self-induction in the primary. The E.M.F. of self-induction at the "break" of the primary is direct, and this added to the E.M.F. of the battery produces a spark at the break points of the circuit breaker.

504. Office of the Condenser. — When the primary circuit of an induction coil is broken, the self-induction tends to sustain the current as if it had inertia; hence it jumps the break as a spark and prevents the abrupt interruption of the primary current, which is essential to high induction in the secondary. The condenser connected across the break gap acts as a reservoir into which the current surges instead of jumping across the break. Thus the spark is nearly eliminated and the secondary E. M. F. increased.

Further, after the break, the condenser, which has been charged by the E.M.F. of self-induction, discharges back through the primary

coil. The condenser thus causes an electric recoil in the current in the reverse direction through the primary, demagnetizing the core and increasing the rate of change of the magnetic flux, and so increasing the E. M. F. in the secondary. Hence, when the secondary terminals are separated, the discharge is all in one direction and occurs when the primary current is broken.

505. Experiments with the Induction Coil. — 1. *Physiological Effects.* — Hold in the hands the electrodes of a very small induction coil, of the style used by physicians. When the coil is working, a peculiar muscular contraction is produced.

The "shock" from large coils is dangerous on account of the high E.M.F. The danger decreases with the increase in the rapidity of the impulses or alternations. Experiments with induction coils, worked by alternating currents of very high frequency, have demonstrated that the discharge of the secondary up to an ampere may be taken through the body without injury.

2. *Mechanical Effects.* — Hold a piece of cardboard between the electrodes of an induction coil giving a spark 3 cm. long. The card will be perforated, leaving a burr on each side. Thin plates of any nonconductor can be perforated in the same manner.

3. *Chemical Effects.* — Place on a plate of glass a strip of white blotting-paper moistened with a solution of potassium iodide (a compound of potassium and iodine) and starch paste. Attach one of the electrodes of a small induction coil to the margin of the paper. With an insulator, handle a wire leading to the other electrode, and when the coil is in action, trace characters with the wire on the paper. The discharge decomposes the potassium iodide, as shown by the blue mark. This blue mark is due to the action of the iodine on the starch.

If the current from the secondary of an induction coil be passed through air in a sealed tube, the nitrogen and oxygen will combine to form nitrous acid. This is the basis of some of the commercial methods of manufacturing nitrogen compounds from the nitrogen of the air.

4. *Heating Effects.* — Figure 433 shows the plan of the "electric bomb." It is usually made of wood. Fill the hole with gun powder

as far up as the brass rods and close the mouth with a wooden ball. Connect the rods to the poles of the induction coil. The sparks will ignite the powder and the ball will be projected across the room.

FIGURE 433. — ELECTRIC BOMB.

The heating effect of the current in the secondary of a large induction coil may be shown by stretching between its poles a very thin iron wire with a small gap in it. The discharge will melt the part connected to the negative pole of the coil, while the other part will remain below the temperature of ignition.

506. Discharges in Partial Vacua. — Place a vase of uranium glass on the table of the air pump, under a bell jar provided with a brass sliding rod passing air-tight through the cap at the top (Fig. 434). Connect the rod and the air pump table to the terminals of the induction coil. When the air is exhausted a beautiful play of light will fill the bell jar. The display will be more beautiful if the vase is lined part way up with tin-foil. This experiment is known as *Gassiot's cascade*. The experiment may be varied by admitting other gases and exhausting again. The aspect of the colored light will be entirely changed.

FIGURE 434. — GASSIOT'S CASCADE.

The best effects are obtained with discharges from the secondary of an induction coil in glass tubes when the exhaustion is carried to a pressure of about 2 mm. of mercury, and the tubes are permanently sealed. Platinum electrodes are melted into the glass at the two ends. Such tubes are known as *Geissler tubes*. They are made in a great variety of forms (Fig. 435), and the luminous effects are more intense in the narrow connecting tubes

than in the large bulbs at the ends. The colors are determined by the nature of the residual gas. Hydrogen glows with a brilliant crimson; the vapor of water gives the same color, indicating that the vapor is dissociated by the discharge. An examination of this glow by the spectroscope gives the characteristic lines of the gas in the tube.

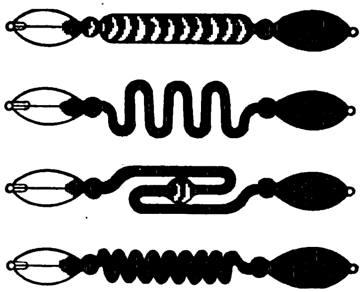


FIGURE 435. — GEISSLER TUBES.

Geissler tubes often exhibit *stratifications*, which consist of portions of greater brightness separated by darker intervals. Stratifications have been produced throughout a tube 50 feet long. These stratifications or striæ present an unstable flickering motion, resembling that sometimes observed during auroral displays.

507. The Discharge Intermittent. — On a disk of white cardboard about 20 cm. in diameter paste disks of black paper 2 cm. in diameter (Fig. 436). Rotate the disk rapidly by means of a whirling table or an electric motor and illuminate it by a Geissler tube in a dark room. The black spots will be sharp in outline because each flash is nearly instantaneous; and the spots in the different circles will either stand still, rotate forward, or rotate backward. If in the brief interval between the flashes the disk rotates through an angle equal to that between the spots in one of the circles, the spots will appear to stand still; if it rotates through a slightly greater angle, the spots will appear to move slowly forward; if through a smaller angle, they will appear to move slowly backward.

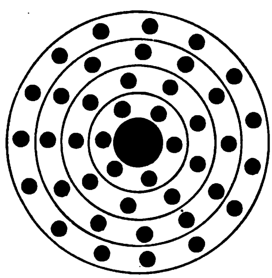


FIGURE 436. — DISK FOR INTERMITTENT ILLUMINATION.

Mount a Geissler tube on a frame attached to the axle of a small electric motor (Fig. 437). Illuminate the tube by an induction coil while it rotates. Star-shaped figures will be seen, consisting of a number of images of the tube, the number depending on the speed of the motor as compared with the period of vibration of the circuit breaker.

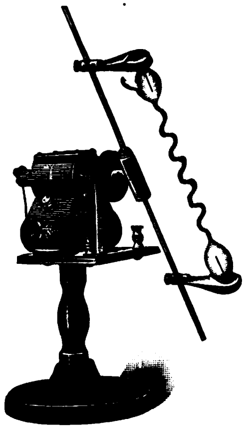


FIGURE 437. — ROTATION OF GEISSLER TUBE.

508. Cathode Rays. — When the gas pressure in a tube is reduced below about a millionth of an atmosphere, the character of the discharge is much altered. The positive column of light extending out from the anode gradually disappears, and the sides of the tube glow with brilliant phosphorescence. With English glass the glow is blue; with German glass it is a soft emerald. The luminosity of the glass is produced by a radiation in straight lines from the *cathode* of the tube; this radiation is known as *cathode rays*. They were first studied by Sir William Crookes, and the tubes for the purpose are called *Crookes tubes*.

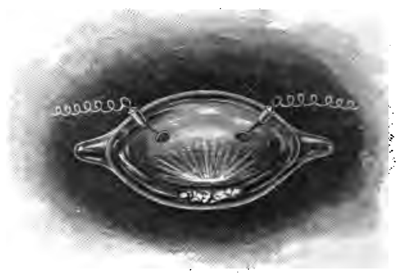


FIGURE 438. — FLUORESCENCE BY CATHODE RAYS.

Many other substances besides glass are caused to glow by the impact of cathode rays (Fig. 438), such as ruby, diamond, and various sulphides. The color of the glow depends on the substance.

Cathode rays have a mechanical effect. In fact they consist of electrons (§ 518) moving with very high velocity approaching that

Sir William Crookes, a distinguished English chemist, was born in 1832. In 1873 he began a series of investigations on the properties of high vacua. While engaged in this work he invented the radiometer, developed the Crookes tubes, and discovered what he called "radiant matter." His investigations led him very close to the discoveries of Röntgen. He has edited the Quarterly Journal of Science since 1864.

Wilhelm Konrad Röntgen was born in 1845. It was at Würzburg, Germany, in 1895, that he discovered while passing electric charges through a Crookes tube, that a certain kind of radiation was emitted capable of passing through many substances known to be opaque to light. The nature of these rays being unknown, he called them "X-rays." They differ from the cathode rays discovered by Crookes, in that they affect a sensitized photographic plate.

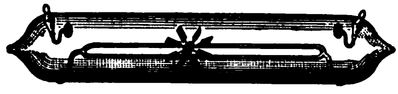


FIGURE 439. — RAILWAY TUBE.

of light. When they strike a target, their motion is arrested and their energy of motion is largely transferred to the target. The light paddle wheel in Figure 439 runs smoothly on glass rails. It may

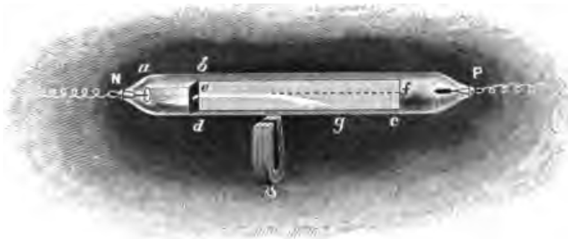


FIGURE 440. — MAGNETIC DEFLECTION OF CATHODE RAYS.

be made to traverse the tube in either direction by projecting electrons from the cathode against the paddles on top. When the cathode is changed from one end to the other by reversing the current in the induction coil, the little wheel stops promptly and reverses its direction. Its paddles are driven as if by a blast from the cathode disk.

FIGURE 441. — FOCUS TUBE.

Cathode rays, unlike rays of light, are deflected by a magnet, and when once deflected they do not regain their former direction (Fig. 440). Cathode rays proceed in straight lines, except as they are deflected by a magnet or by mutual repulsion. A screen placed across their path interrupts them and casts a shadow on the walls of the tube.

When the cathode is made in the form of a concave cup, the rays are brought to a focus near its center of

curvature; platinum foil placed at this focus is raised to bright incandescence and may be fused (Fig. 441). Glass on which an energetic cathode stream falls may be heated to the point of fusion.

It has been conclusively shown that cathode rays carry negative charges of electricity. Hence the mutual repulsion exerted on each other by two parallel cathode streams.

509. Roentgen Rays. — The rays of radiant matter, as Crookes called it, emanating from the cathode, give rise to another kind of rays when they strike the walls of the tube, or a piece of platinum placed in their path. These last rays, to which Roentgen, their discoverer, gave the name of "*X-rays*," can pass through glass, and so get out of the tube. They also pass through wood, paper, flesh, and many other substances opaque to light. They are stopped by bones, metals (except in very thin sheets), and by some other substances. Roentgen discovered that they affect a photographic plate like light. Hence, photographs can be taken of objects which are entirely invisible to the eye, such as the bones in a living body, or bullets embedded in the flesh.

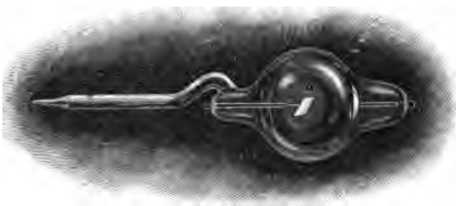


FIGURE 442. — ROENTGEN TUBE.

A Crookes tube adapted to the production of Roentgen rays (Fig. 442) has a concave cathode K, and at its focus an inclined piece of platinum A, which serves as the anode. The X-rays originate at A and issue from the side of the tube.

510. X-Ray Pictures. — The penetrating power of Roentgen rays depends largely on the pressure within the tube. With high exhaus-

tion the rays have high penetrating power and are then known as "hard rays." Hard rays can readily penetrate several centimeters of wood, and even a few millimeters of lead. With somewhat lower exhaustion, the rays are less penetrating and are then known as "soft rays."

The possibility of X-ray photographs depends on the variation in the penetrability of different substances for X-rays. Thus, the bones of the body absorb Roentgen rays more than the flesh, or are less penetrable by them. Hence fewer rays traverse them. Since Roentgen rays cannot be focused, all photographs taken by them are only shadow pictures. A Roentgen photograph of a gloved hand is shown in Figure 443. The ring on the little finger, and the cuff studs are conspicuous. The flesh is scarcely visible because of the high penetrating power of the rays used. The photographic plate for the purpose is inclosed in an ordinary plate holder and the hand is laid on the holder next to the sensitized side.

FIGURE 443. — X-RAY PICTURE.

511. The Fluoroscope. — Soon after the discovery of X-rays it was found that certain fluorescent substances, like platino-barium-cyanide, and calcium tungstate, become luminous under the action of X-rays. This fact has been turned to account in the construction of a *fluoroscope* (Fig. 444), by means of which shadow pictures of concealed objects become visible. An opaque screen is

covered on one side with the fluorescent substance; this screen fits into the larger end of a box blackened inside, and having at the other end an opening adapted to fit closely around the eyes, so as to exclude all outside light. When an object, such as the hand, is held against the fluorescent screen and the fluoroscope is turned toward the Roentgen tube, the bones are plainly visible as darker objects than the flesh because they are more opaque to X-rays. The beating heart may be made visible in a similar manner.

FIGURE 444. — FLUOROSCOPE.

IV. RADIOACTIVITY AND ELECTRONS

512. Radioactivity. — Wrap a photographic plate in black paper. Flatten a Welsbach mantle and lay it on the paper next to the film side of the plate. Place the whole in a light-tight box for about a week. If the plate be now developed, a photographic picture of the mantle will appear on it.

The mantle contains the rare metal thorium. This metal possesses the property of emitting all the time radiations that act like X-rays on a photographic plate. Substances having this property are known as *radioactive.* The principal ones are uranium, polonium, actinium, thorium, radium, and their compounds.

513. Discovery of Radioactivity. — The activity of X-rays in producing photographic changes led directly to the discovery of the radioactivity of uranium by Becquerel in 1896. He found that uranium salts give off spontaneously radiations capable of passing through black paper and thin

Madame Marie Sklodowska Curie was born in Warsaw in 1867. She imbibed the spirit of scientific research from her father, a distinguished physicist and chemist. In 1895 she married Professor Curie of the University of Paris. Three times she has been awarded the Gegner prize by the French Academy for her valuable contributions to the world's knowledge of the magnetic properties of iron and steel and for her discoveries in radioactivity. In 1903 and again in 1911 the Nobel prize was awarded her. In January of 1911 she failed only by two votes of election to membership in the French Academy of Sciences, being defeated by Branley, the inventor of the coherer used in the Marconi system of wireless telegraphy.

sheets of aluminum foil, and that they affect photographic plates as X-rays do. These radiations are not modified in any way by the most drastic treatment of the uranium, whether by heat or cold or other physical changes.

514. Radium. — Two years after Becquerel's discovery Madame Curie found in pitchblende (an impure oxide of uranium) a constituent much more highly radioactive than uranium itself. She succeeded by chemical means in extracting this remarkable substance from pitchblende and named it *radium*.

Radium is a million times more radioactive than uranium. Although widely distributed, the total quantity of radium in the earth is undoubtedly small. It takes 150 tons of pitchblende to furnish one ounce of radium. It is a hard white metal, resembling barium. It is very unstable and is usually prepared and used as a chloride or a bromide. Its radiations excite strong fluorescence in several substances, notably zinc sulphate, diamond, and ruby; and they produce on the human body sores difficult to heal.

515. Three Kinds of Radium Rays. — Rutherford has shown that radium emits three kinds of "rays," which can be separated by means of a strong magnetic field. Their difference in behavior in a magnetic field is illustrated in Figure 445. The radium is placed at the bottom of a small hole in a block of lead, so that only a thin pencil of rays escapes in a vertical direction. A strong magnetic field is applied so that the lines of force run away from the observer. The radiations are then separated into three kinds, known as *alpha*, *beta*,

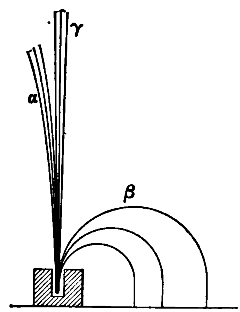


FIGURE 445. — ALPHA, BETA, AND GAMMA RAYS.

and *gamma* rays. The *alpha* rays are slightly deflected to the left, the *beta* rays strongly to the right, while the *gamma* rays are not affected in the least. The fact that the *alpha* and *beta* rays suffer deviations in opposite directions shows not only that they are charged particles, but that they are oppositely charged, the former positively and the latter negatively.

The *alpha* rays are positively charged particles emitted with an average velocity about one-fifteenth the speed of light. They have little penetrating power and are absorbed by a sheet of ordinary writing paper.

The *beta* rays are negatively electrified, highly penetrative, and identical in nature with cathode rays (§ 508). They travel with an average speed from about one-half down to about one-tenth that of light.

The *gamma* rays are of very high penetrating power, they travel with the velocity of light, and appear to be identical with X-rays. They show no trace of electrification.

516. Radium a Product of Disintegration. — Uranium has the highest atomic weight of any known substance, and it is always associated in nature with other radioactive substances. This association suggested that the other radioactive substances are derived from uranium by its disintegration, or loss of particles with reduction of atomic weight. Such has been found to be the case. Uranium is the parent of ionium, and ionium is the parent of radium. Radium is thus a product of disintegration.

Further, the radium atom disintegrates with the expulsion of an *alpha* particle ; and the *alpha* particle, after losing its positive charge, becomes an atom of ***helium***. Thus a known element is produced during the transformation of radioactive matter. All *alpha* particles from whatever source consist of helium atoms carrying positive charges.

Sir Joseph John Thomson was born near Manchester, England, in 1856. He received his early training at Owens College, and acquired there some knowledge of experimental work in the laboratory of Balfour Stewart. At the age of twenty-seven he was appointed to the Cavendish professorship at the University of Cambridge, a position made famous by Maxwell and Rayleigh. The wisdom of the appointment was soon proved; for shortly after, Thomson began a series of experiments on the conduction of electricity through gases, culminating in the discovery of the "electron," out of which has developed the electron theory of matter.

Evidence derived from the study of uranium minerals makes it almost certain that the final product of the disintegration of uranium is lead.

517. Heat Generated by Radium. — The salts of radium exhibit an altogether new and remarkable property; they are always maintained at a temperature several degrees higher than that of the surrounding air. They are thus always radiating heat and giving out energy. A gram of pure radium would emit heat at the rate of from 100 to 130 calories per hour. It has been estimated that before a gram of radium is exhausted it would emit enough heat to melt a gram of ice every hour for 1000 years. Also, that the energy of radium is a million and a half times greater than that of an equal mass of coal.

518. Electrons. — Sir William Crookes, at the time of his discovery of the cathode discharge, regarded it as matter in a *radiant* state. Later it was demonstrated that the cathode discharge carries negative electricity. Still later, by a series of brilliant experiments, Sir J. J. Thomson proved that cathode "rays" consist of streams of negatively electrified particles, now called *electrons*. The mass of an electron is only about $\frac{1}{1800}$ of the mass of the hydrogen atom. Moreover, he measured their speed in a vacuum and found it to have the enormous value of about 50,000 miles per second.

The electron is invariable in magnitude, and is said to be "the atom of electricity," that is, the smallest quantity of electricity that can be transferred from one atom of matter to another. It is the smallest quantity that exists in a separate state.

The *beta* rays spontaneously emitted by radium and other radioactive matter have now been identified with the electrons of a Crookes tube. There is good evidence also that

the electron is identical with the single atomic charge of a negative ion in electrolysis. If positive electricity is atomic, its atom is several thousands of times greater than the atomic quantity of negative electricity.

Electrons enter into the composition of all matter. An electric current is supposed to be a stream of electrons flowing under electric pressure through a conductor from negative to positive.

CHAPTER XIV

DYNAMO-ELECTRIC MACHINERY

I. DIRECT CURRENT MACHINES

519. A Dynamo-Electric Generator is a machine to convert mechanical energy into the energy of currents of electricity. It is a direct outgrowth of the brilliant discoveries of Faraday about induced electromotive forces and currents in 1831. It is an essential part of every system, steam or hydro-electric, for electric lighting, the transmission of electric power, electric railways, electric locomotives, electric train lighting, the charging of storage batteries, electric smelting, electrolytic refinement of metals, and for every other purpose to which large electric currents are applied.

520. Essential Parts of a Dynamo-Electric Machine. — Every dynamo-electric machine has three essential parts: 1. The *field magnet* to produce a powerful magnetic field. 2. The *armature*, a system of conductors wound on an iron core, and revolving in the magnetic field in such a manner that the magnetic flux through these conductors varies continuously. 3. The *commutator*, or the *collecting rings* and the *brushes*, by means of which the machine is connected to the external circuit. If the magnetic field is produced by a permanent magnet, the machine is called a *magneto*, such as is used in an automobile for ignition; if by an electromagnet, the machine is a *dynamo*, which is used in electric lighting stations, and for all other purposes requiring large currents generated by high power. Both are often called *generators*.

521. Ideal Simple Dynamo. — For the purpose of simplifying what goes on in the revolving coils of a generator, let us consider a single loop of wire revolving between the poles of a magnet (Fig. 446) in the direction of the arrow and around a horizontal axis. The light lines indicate the magnet flux running across from *N* to *S*. In the position of the loop drawn in full lines it incloses the largest possible magnetic flux or lines of force, but as the flux inclosed by the coil is not changing, the induced E.M.F. is zero.

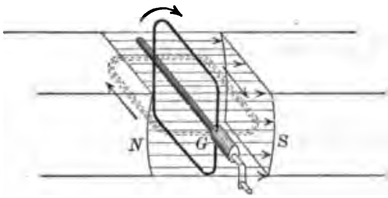


FIGURE 446. — IDEAL SIMPLE DYNAMO.

When it has rotated forward a quarter of a turn, its plane will be parallel to the magnetic flux, and no lines of force will then pass through it. During this quarter turn the decrease in the magnetic flux, threading through the loop, generates a direct E.M.F.; and if the rotation is uniform, the *rate of decrease* of flux through the loop increases all the way from the first position to the one shown by the dotted lines, where it is a maximum. The arrows on the loop show the direction of the E.M.F.

During the next quarter turn there is an increase of flux through the loop, but it runs through the loop in the opposite direction because the loop has turned over; this is equivalent to a continuous decrease in the original direction, and therefore the direction of the induced E.M.F. *around the loop* remains the same for the entire half turn; the E.M.F. again becomes zero when the half turn is completed.

After the half turn, the conditions are all reversed and the E. M. F. is directed the other way around the loop.

If there are several turns in the coil, the E. M. F. reverses in all of them twice every revolution.

The curve of Figure 447 shows by its ordinates the successive relative values of the induced electromotive forces when the coil rotates with uniform speed. If the coil is part of a closed circuit, the current through it reverses twice every revolution, that is, it is an alternating current.

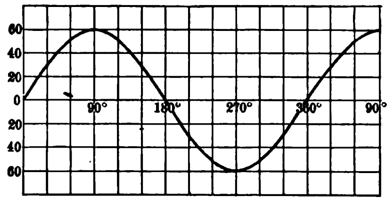


FIGURE 447. — CURVE OF E. M. F.'s.

522. The Commutator. — When it is desired to convert the alternating currents flowing in the armature into a current in one direction through the external circuit, a special device called a *commutator* is employed. For a single coil in the armature, the commutator consists of two parts only. It is a split tube with the two halves, *a* and *b*, insulated from each other and from the shaft *S* on which they are mounted (Fig. 448). The two ends of the coil (not shown) are connected with the two halves of the tube.

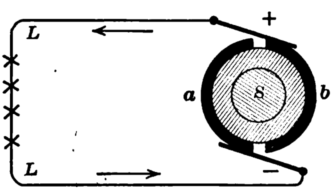


FIGURE 448. — TWO-PART COMMUTATOR.

Two brushes, with which the external circuit *L L* is connected, bear on the commutator, and they are so placed that they exchange contact with the two commutator segments at the same time that the current reverses in the coil. In this way one of the brushes is always positive and the other negative, and the current flows in the external circuit from the positive brush back to the

negative, and thence through the armature to the positive again; but with a single coil the current is pulsating, or falls to zero twice every revolution (Fig. 449).

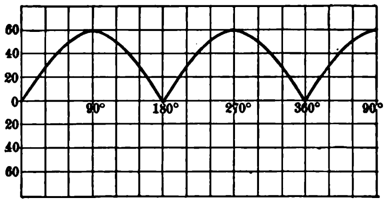


FIGURE 449. — RECTIFIED E. M. F.'s.

523. The Gramme Ring. — The use of a commutator with more than two parts is conveniently illustrated in connection with the *Gramme ring*. This armature has gone out of practical use, but it is useful here because it can be understood from a simple diagram; and fundamentally its action is the same as that of the common drum type.

The Gramme ring has a core made either of iron wire, or of thin disks at right angles to the axis of rotation. The iron is divided for the purpose of preventing induction or *eddy* currents in it, which waste energy. The relation of the several parts of the machine is illustrated by Figure 450. A number of coils are wound in one direction and are all joined in series. The coils must be grouped symmetrically so that some of them are always active, thus generating a continuous current. Each junction between coils is connected with a commutator bar. Most of the magnetic flux passes through the iron ring from the north pole side to the south pole; hence, when a coil is in the highest position in the figure, the maximum flux passes through it; as the ring rotates, the flux through the

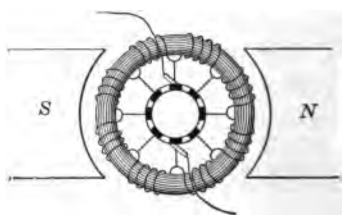


FIGURE 450. — THE GRAMME RING.

coil decreases, and after a quarter of a revolution there is no flux through it. The current through each coil reverses twice during each revolution, exactly as in the case of the single loop. No current flows entirely around the armature, *because the E.M.F. generated in one coil at any instant is exactly counterbalanced by the E.M.F. generated in the coil opposite.* But when the external circuit connecting the brushes is closed, a current flows up on both sides of the armature. The current has then two paths through the armature, and one brush is constantly positive and the other negative. The current is therefore *direct* and fairly steady.

524. The Drum Armature. — This very useful form of armature is in universal use for direct current (D. C.) generators. The core is made up of thin iron disks stamped out with teeth around the periphery (Fig. 451). When these are assembled on the shaft, the slots form grooves in which are placed the armature windings. All the coils in the armature may be joined in series, and the junctions between them are connected to the commutator bars, as in the Gramme ring.

FIGURE 451. — TOOTHED DISK.

525. The Field Magnet. — The magnetic field in dynamos is produced by a large electromagnet excited by the current flowing from the armature; this current is led, either wholly or in part, around the field-magnet cores. When the entire current is carried around the coils of the field magnet, the dynamo is said to be *series wound* (Fig. 452 *a*). When the field magnet is excited by coils of many turns of fine wire connected as a shunt to the external circuit, the dynamo is said to be *shunt wound* (Fig. 452 *b*). A combination of these two methods of exciting

the field magnet is called *compound winding* (Fig. 452 *c*). The residual magnetism remaining in the cores is sufficient to start the machine. The current thus produced

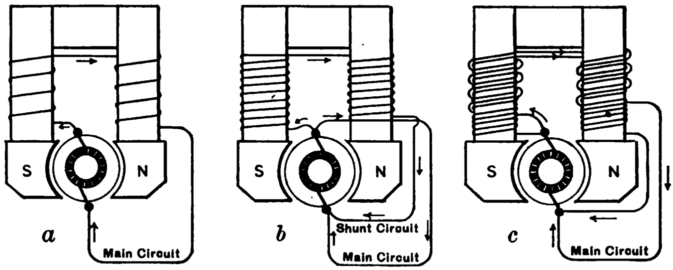
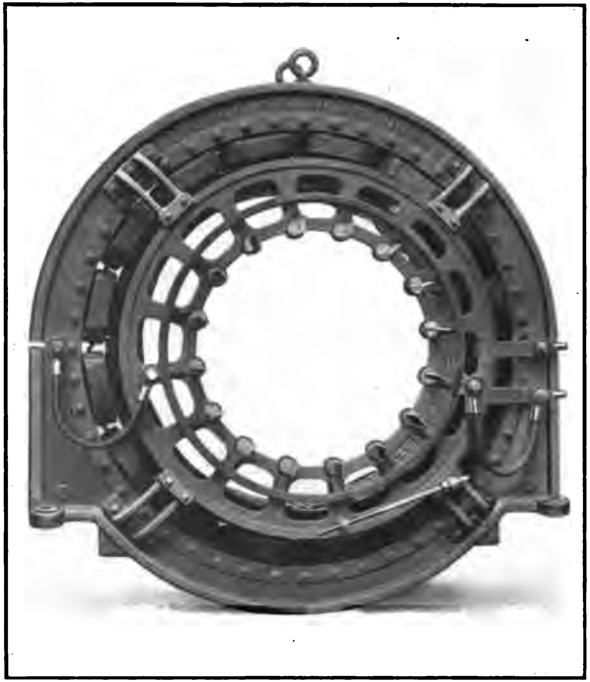


FIGURE 452. — FIELD MAGNET WINDINGS.

increases the magnetic flux through the armature and so increases the E.M.F.

526. The Modern Generator. — Large modern D. C. generators are multipolar, with four, six, or eight, or more poles. The larger number of poles reduces the rate of rotation of the armature. In the field magnet shown in the half tone on the opposite page there are sixteen poles, north poles and south poles alternating around the ring. The armature is wound in loops which reach across a chord nearly equal to the pitch of the poles, so that when one side of a loop is passing a north pole, the opposite side is passing an adjacent south pole. In a simple drum armature there are as many brushes as there are field poles, and there are the same number of parallel paths or circuits through the windings as there are brushes. An engine type of multipolar drum armature is shown in the illustration on the opposite page.

527. The Electric Motor. — The *electric motor* is a machine for the conversion of the energy of electric currents into mechanical power.



Field Magnet of D. C. Generator.

Drum Armature of D. C. Generator.

In the electric automobile and in the electric starter for gasoline machines the motor is driven by currents from a storage battery. In the electric street car it derives its current and power from a trolley, a third rail, or from conductors fixed in a slotted conduit under the pavement, all of them leading back to a power house or a substation. The electric motor is extensively used for small power as well as for large units. Witness the use of electric fans, electric coffee grinders, sewing machine motors, and electrically driven bellows for pipe organs on one hand, and on the other the electric drive for large fans to ventilate mines and buildings, electric elevators, and electrically driven mills and factories.

An electric motor for direct currents is constructed in the same manner as a generator. In fact, any direct current generator may be used as a motor. A study of the magnetic field resulting from the interaction of the field due to the field magnet and that of a single loop carrying an electric current will make it clear that such a loop has a tendency to rotate.

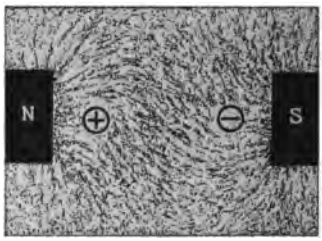


FIGURE 453. — MAGNETIC FIELD DISTORTED BY CURRENT.

Figure 453 was made from a photograph of the field shown by fine iron filings between unlike poles. This field is distorted by a current through a loop of wire, which came up through the hole on the right in the glass plate and went down through the other. Many of the lines of force are threaded through the wire loop instead of running directly across from one magnetic pole to the other. Now the lines of magnetic force are under tension and tend to straighten out; this straightening brings a magnetic stress to bear on the loop carrying the current and tends to turn it counter-clockwise in the case shown in the figure.

If the loop be allowed to rotate in the direction of this magnetic effort between the field and the loop, the loop will become the armature of a motor and work will be done by the machine at the expense of the energy of the current flowing through it. If, however, the loop be forcibly rotated clockwise by mechanical means, it will turn against the magnetic effort acting on it, and work will be done against the resistance of this magnetic drag. The loop will then be the armature wire of a generator.

528. Forms of D. C. Motors. — Since any D. C. generator will run as a motor, we find D. C. motors either series or shunt wound according to the service for which they are designed. *Series wound motors* are used on street cars and electric automobiles, where the service requires variable speed. *Shunt wound motors* are used to run machinery in shops and factories, where constant speed is desirable. High speed motors are usually bipolar; motors for slow speed service have multipolar fields.

The torque, or turning moment, of an electric motor depends both upon the strength of the magnetic field and the current through the armature. In a shunt wound motor the field strength is nearly constant; hence the torque varies directly as the current through the armature. In a series motor, on the other hand, the strength of field varies nearly as the current, and the current is the same through the field and the armature. Hence the torque varies as the square of the current. If the current is doubled, it is doubled in both the field and the armature, and the torque is therefore quadrupled. The series motor is accordingly used where a large starting torque is required, as in cranes and motor vehicles.

529. Back E.M.F. in a Motor. — Connect an incandescent lamp on the lighting circuit *in series* with a small motor. Clamp the armature or hold it stationary, and turn on the current. The lamp will glow with full brilliancy. Next let the motor run at full speed without load; the lamp will now grow dim.

If the motor is provided with a flywheel to keep up its motion when the current is shut off, the lamp and the motor may be connected to the mains *in parallel.* Then when the motor is running at full speed, the lamp will glow with nearly or quite normal brilliancy. Now open the switch, cutting off both the lamp and the motor from the mains; the lamp will glow for a few seconds nearly as brightly as before the main circuit was opened.

The first experiment shows that the motor running takes less current than when the armature is held fast. But since the resistance in circuit remains unchanged, the lessened current by Ohm's law must be ascribed to a smaller E.M.F. The fact is, the motor produces a back E.M.F. nearly equal to the applied E.M.F. Denote the back E.M.F. by E'; then by Ohm's law

$$I = \frac{E - E'}{R}.$$

Since the current is small when the motor is running, E' must be nearly equal to E.

The second experiment shows the back E.M.F. directly, for it lights the lamp so long as the motor is kept running by the energy stored in the flywheel after shutting off both the lamp and the motor from the supply mains. The armature revolves in a magnetic field and generates an E.M.F. for the same reason that it does when spun as a generator.

530. Starting Resistance. — The resistance of a motor armature is small, and a motor at rest has no back E.M.F. to limit the current. If therefore the current were turned on without temporary starting resistance in

circuit, there would be a great rush of current, which might damage the motor, blow the line fuses, and possibly throw open the automatic circuit breaker in the power house. Hence the use of a starter, which is a rheostat with a number of graduated resistances (Fig. 454). When the switch arm is turned to touch the first live contact point, the circuit is closed through enough resistance to avoid danger. As the motor speeds up and generates larger and larger back E.M.F., the resistance is gradually cut out by moving the switch arm to successive contact points, until the starting resistance is all out and the motor is running at full speed. In the figure A is the armature and F the field coil of a shunt motor.

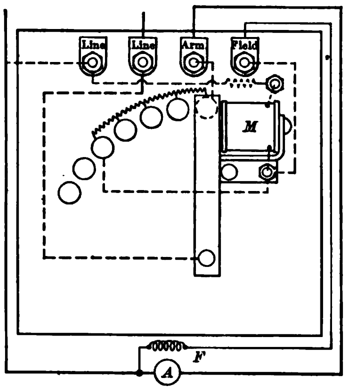


FIGURE 454. — STARTING RESISTANCE FOR MOTOR.

The switch arm is often held in place by a release magnet M after the entire starting resistance is cut out. If the line switch is opened, or the circuit broken in any other way, the magnet releases the arm and a spring throws it back to open circuit. This prevents injury if the current should suddenly come on again.

531. Electric Railways. — The electric current is usually conveyed to the moving car by trolley wire, a third rail, or by a conductor laid in a slot-conduit between the rails. Direct current under an electric pressure of 550 volts is nearly always used. A feeder wire is often employed to prevent too great a drop in voltage at distant points

(Fig. 455). The circuit is from the positive brush of the generator to the feeder and trolley wires or third rail, thence through the motors to the car wheels and track, and so back to the negative terminal of the generator.

Each car is equipped with two series wound, four-pole motors. They drive the wheels through a single reduction gear. At starting, the "controller" or start-

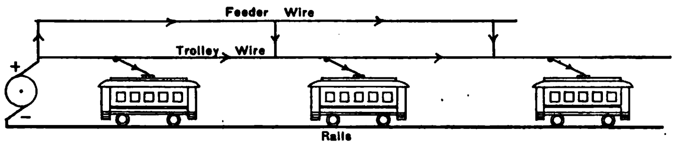


FIGURE 455. — ELECTRIC RAILWAY AND FEEDER.

ing rheostat places the two motors in series with some resistance. After the car has started, this resistance is first cut out; then the motors are joined in parallel with resistance in circuit; this resistance is finally cut out after the car attains sufficient speed. As the motor speeds up it generates a back-electromotive force, which reduces the current to its working value.

II. ALTERNATORS AND TRANSFORMERS

532. The Alternator. — If the ends of the armature coil are connected to two *slip-rings* (Fig. 456) by which sliding contact is made with the brushes A and B and the external circuit, the machine becomes an *alternator*, and the current flowing in the external circuit CD will alternate or reverse, as it does in an armature coil, every time the armature turns through the angular distance from one pole to the next.

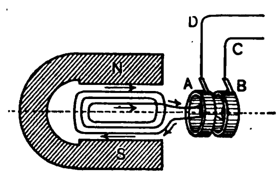


FIGURE 456. — SLIP-RINGS.

A complete series of changes in the current and E.M.F. in both directions takes place while the armature is turning from one pole to the next one of the same name. Such a series of changes is called a *cycle*. The *frequency*, or the number of cycles per second, is equal to the product of the number of pairs of poles on the field magnet and the number of rotations per second. Frequencies are now restricted between the limits of about 25 and 60 cycles per second. Multipolar machines are used to avoid excessive speed of rotation.

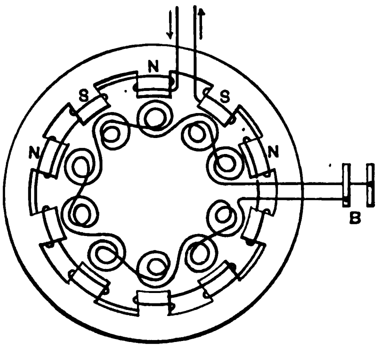
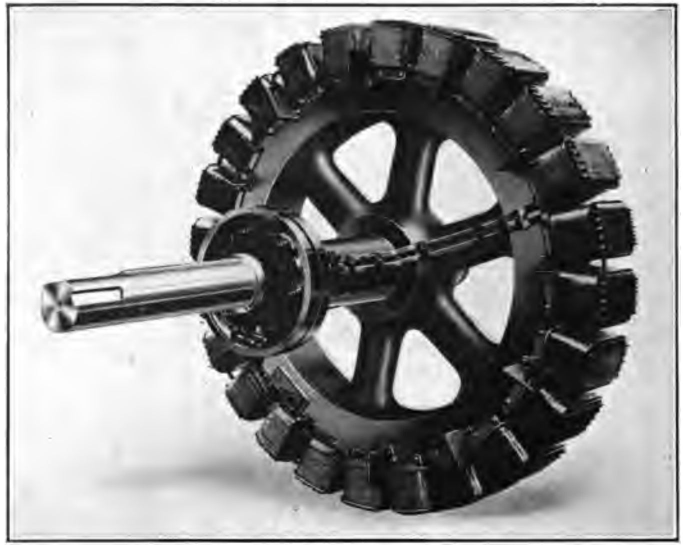


FIGURE 457. — ALTERNATOR WITH STATIONARY FIELD.

Figure 457 is a diagrammatic sketch of an alternator with a stationary field outside and an armature rotating with the shaft. The field is excited by a small direct current machine called the *exciter*. The armature coils are reversed in winding from one field pole N to the next S, they are joined in series, and the terminals are brought out to rings B on the shaft. The brushes bearing on these rings lead to the external circuit.

533. Alternators with Rotating Field. — Since the rotation of the armature with respect to the field is only relative, it clearly makes no difference in the generation of E.M.F. whether the armature or the field is made the rotating member. In large alternators (A. C. generators) the armature is the stationary member outside and the field rotates within. Slow speed generators necessarily have a large number of poles. This construction follows the

Armature Core of A. C. Generator.



Field Magnet of A. C. Generator.

best engineering practice, since it permits better insulation of the armature windings on the stationary member of the machine and avoids the transmission of high voltages by sliding contacts on slip rings.

The armature core is built up from punchings of selected steel of superior magnetic quality; these punchings are coated with insulating varnish to reduce eddy current losses. The armature punchings are securely bolted together between two cast-iron rings having an I-beam section. Air ducts are left in the core for the purpose of ventilation.

534. Lag of Current Behind E.M.F. — When the circuit has self-inductance, an alternating E.M.F. produces a current which lags behind the E.M.F.; and as a consequence Ohm's law is no longer adequate to express its value. The self-inductance not only introduces an additional E.M.F., but it causes the current to come to its maximum value later than the E.M.F. impressed on the circuit by the generator.

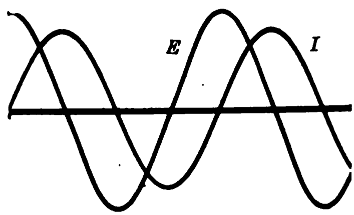


FIGURE 458. — LAG OF CURRENT BEHIND E. M. F.

Figure 458 is reproduced from a photograph made by the E.M.F. and currents themselves in an instrument called an oscillograph. It is a kind of double galvanometer in which the movable systems have so short a period that they can follow all the oscillations of the current and E.M.F. A beam of light is reflected from a tiny mirror in the instrument and acts on a rapidly moving photographic plate. *E* in the figure is the curve of the impressed E.M.F. and *I* that of the current. The latter in this case came to its maximum nearly a quarter

of a period later than the former. (Trace the curves from left to right.)

535. Polyphase Alternators. — Two or more currents of the same frequency, but differing in phase (§ 196), may be obtained from one generator. Two-phase or three-phase currents are specially useful for the transmission of power and for driving induction motors; at the same time they are just as useful for lighting purposes as the current from a single-phase machine.

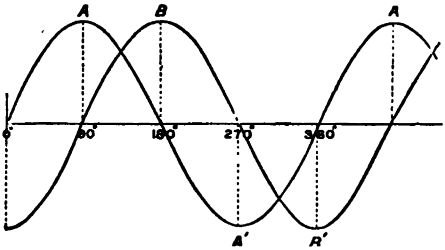


FIGURE 459. — TWO-PHASE CURRENTS.

In a two-phase alternator there are two sets of windings, the one set being displaced from the other by half the pole pitch; the two electromotive forces induced in them in consequence differ by a quarter of a period (Fig. 459). When one of these electromotive forces passes through zero value, the other will be at its maximum.

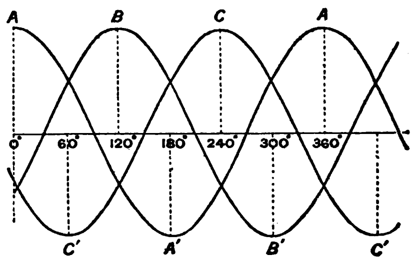


FIGURE 460. — THREE-PHASE CURRENTS.

In a three-phase alternator there are three separate sets of windings, displaced from one another by two-thirds of the pole pitch. There are generated three electromotive forces of equal amplitude, but differing in phase by one-third of a period

(Fig. 460). The three-phase system is best adapted to the transmission of power. Three lines only are needed instead of six. If one end of each winding is brought to a common junction, and the other ends are connected respectively to the three lines, no return is needed, since each line in succession serves as the return for the other two. This may be understood from an examination of Figure 460, which shows that the sum of the two currents or electromotive forces in one direction at any instant is always equal to the third in the other direction; in other words, the algebraic sum of the three is always zero.

536. Transformers. — A *transformer* is an induction coil with a primary of many turns of wire and a secondary of a smaller number, both wound around a divided iron core forming a closed magnetic circuit; that is, one magnetic circuit is interlinked with two electric circuits (Fig. 461). A transformer is employed with alternating currents either to step down from a high E.M.F. to a low one, or the reverse. The two electromotive forces are directly proportional to the number of turns of wire in the two coils.

FIGURE 461. — TRANSFORMER.

For example, to reduce a 2000-volt current to a 100-volt current, there must be 20 turns in the primary to every one in the secondary. Both coils are wound on the same iron core, and are as perfectly insulated from each other as possible. The iron serves as a path for the flux of magnetic induction, and all the lines of force produced by either coil pass through the other, except for a small amount of "magnetic leakage." When the secondary is open, the

transformer acts simply as a "choke coil"; that is, the self-induction of the primary is so large that only sufficient current is transmitted to magnetize the iron and to furnish the small amount of energy lost in it.

The counter-E.M.F. of self-induction is then nearly equal to the E.M.F. impressed from without. But when the secondary is closed, the self-induction is suppressed to the extent that the transformer automatically adjusts itself to the condition that the energy in the secondary circuit lacks only a few per cent of the energy absorbed by the primary from the generator.

537. Transformers in a Long-distance Circuit. — The utility of the transformer lies in its use to secure high voltage for transmission and low voltage for lighting and power. Only small currents can be transmitted over distances exceeding a few hundred feet without excessive heat losses

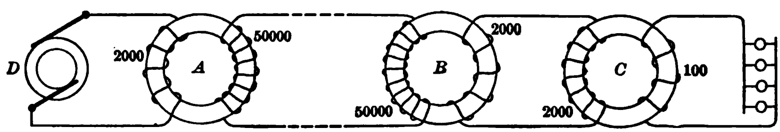


FIGURE 462. — TRANSFORMERS ON LONG-DISTANCE CIRCUIT.

on account of the resistance of the conductors. To transmit power while still keeping the current small, the electric pressure, that is, the number of volts, must be increased, for power transmitted in watts is proportional to the product of the number of volts and the number of amperes.

Figure 462 is a diagram showing a transformer system for long-distance power transmission. The first transformer *A* raises the potential difference from 2000 volts to 50,000 volts. The long distance transmission takes place at this voltage to the second transformer *B*, which steps down from 50,000 to 2000 volts for local transmis-

sion within the limits of a city or a district. The third transformer C steps down further from 2000 to 100 volts for house service for lighting, fan motors, electric cooking, electric flatirons, etc.

538. Long Distance Transmission of Power. — Power is now transmitted over long distances by means of alternating currents of high voltage. The transmission is invariably

FIGURE 463. — CABLES AND TOWERS OF 150,000-VOLT LINE.

by three-phase currents over one or two sets of copper or aluminum cables, strung on steel towers at a height of about 75 feet. These cables run straight from point to point over mountains, valleys, and streams. For example, the electric power generated by the hydro-electric plants

at Niagara Falls is raised by step-up transformers to 60,000 volts for transmission to distant cities, — Buffalo, Rochester, Syracuse, where it is used for street car service, for power motors, and for lighting and other domestic purposes.

At Big Creek in the High Sierras in California, water power to the extent of 80,000 H. P. is now used for generating three-phase electric currents; the voltage is raised by step-up transformers to 150,000 for transmission over aluminum cables 241 miles to the Eagle Rock transformer station. These cables are 0.96 inch in diameter, and are strung 17.5 feet apart, on steel towers averaging seven to the mile. At present two sets of three-wire cables are in use, each set strung on separate towers (Fig. 463). Ultimately there will be three sets for the transmission of 320,000 H. P.

At Eagle Rock step-down transformers reduce the electric pressure to 15,000 volts for transmission over the Los Angeles district, and to 60,000 volts for the Riverside district and beyond. The latter district adds about 80 miles to the transmission, making 320 miles as a maximum.

539. The Rotating Magnetic Field. — It is of first importance to understand how a magnetic field may rotate while the coils producing the field stand still; for the rotating field, invented by Ferraris and Tesla, is the secret of all A. C. induction motors for two- or three-phase currents. A simple experiment will help to clear up the problem.

Suspend a heavy ball by a string at least ten feet long and set it swinging north and south with an amplitude of a foot or more. At the instant when the ball stops at either extremity of its path, strike it a blow with a mallet east and west. This blow will cause an east and west simple harmonic motion, differing in phase from the north

and south one by a quarter of a period. Further, if the blow is delivered with the right force, the two simple harmonic motions, combined in the pendulum, will give rise to uniform circular motion of the ball.

This experiment shows that uniform circular motion may be produced by combining two simple harmonic motions at right angles to each other, of the same period and amplitude, and differing in phase by a quarter of a period.

An alternating current in a coil without iron produces an alternating magnetic field along the axis of the coil. If the current follows the simple harmonic or sine law, the magnetic field will follow it also.

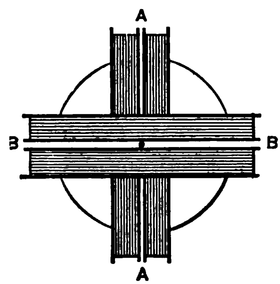


FIGURE 464. — COILS FOR ROTATING FIELD.

Let two like coils be set with their axes at right angles (Fig. 464), and let two-phase currents be passed through them, one through coil *AA* and the other through *BB*. Now these two magnetic fields produced by the two-phase currents are similar to the two motions of the ball in the pendulum experiment; and they combine to produce a rotating magnetic field near their common center. A small magnetic needle mounted there will spin around rapidly. This is analogous to the way in which uniform rotary motion without dead points may be produced from two oscillatory motions by using two cranks at right angles, as in quarter-crank engines, the one impulse following the other at one fourth of a period.

The above combination of two coils at right angles is suitable for *two-phase* currents only. Another way to

make a rotating magnetic field is by *three-phase* currents. These differ in phase by one third of a period (or 120°). They are analogous to a three-crank engine with the cranks set at angular distances of 120°.

540. Ways of Combining the Circuits. — The coils or circuits that receive the polyphase currents may be combined in several ways. In Figure 465 for a two-phase system, the entire ring is wound as a closed circuit like a Gramme ring, and the four line wires are attached at four equidistant points. Instead of this plan, the winding may be divided into four separate coils, all having corresponding ends connected to a common junction, the other four ends being joined to the four line wires, AA' for one circuit and BB' for the other.

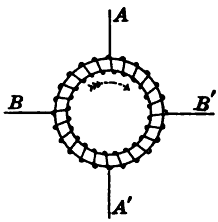


FIGURE 465.—WINDING FOR TWO-PHASE ROTATING FIELD.

For a three-phase system Figure 466 shows the *mesh* or Δ method of connection. Again the three coils may have a corresponding end of each connected to a common junction, the other ends remaining for the three line wires. This is known as the *star* or *Y*-connection.

Again, the coils may not be wound upon a ring, but on poles projecting inward. In large multipolar machines the three-phase coils may be wound on six, nine, or a larger number of poles, multiples of three, or they may be embedded in slots as in the armature or *stator* of A. C. generators.

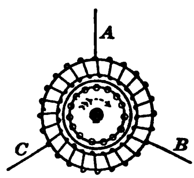
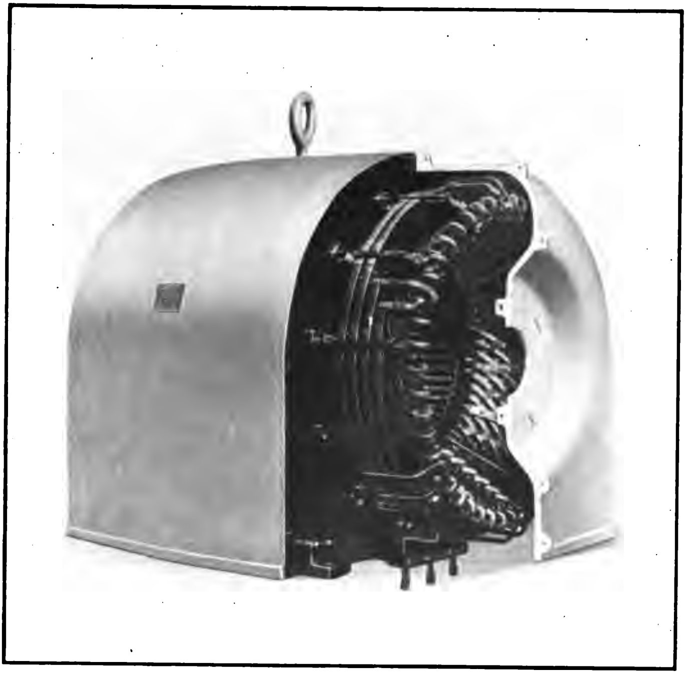
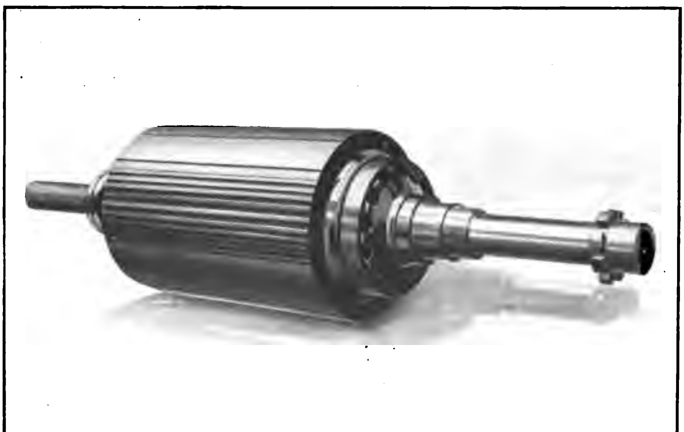


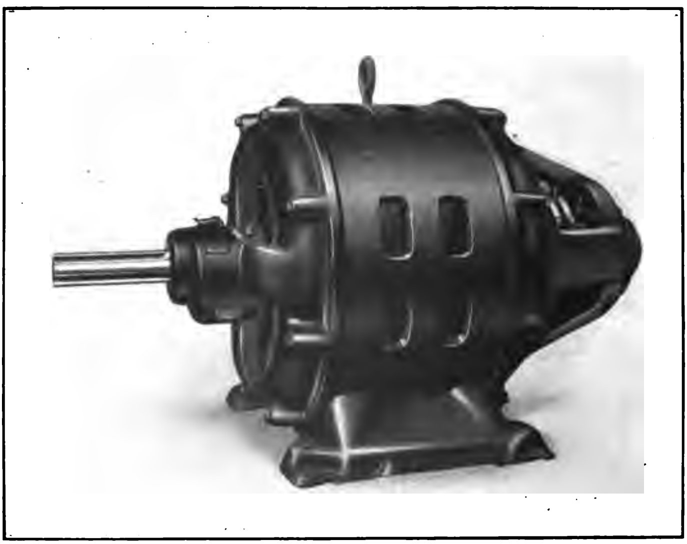
FIGURE 466.—WINDING FOR THREE-PHASE ROTATING FIELD.

541. Induction Motors. — In 1888 Ferraris of Italy mounted within coils like those of Figure 464 a hollow copper cylinder on pivots at top and bottom. When two-phase





Above: Stator of A. C. Generator Connected to Steam Turbine.
Below: Field of the Same.



ABOVE: STATOR OF THREE-PHASE MOTOR.
BELOW: THREE-PHASE MOTOR COMPLETE.

currents are passed through the two circuits of the Ferraris apparatus, the copper cylinder is set rotating in the direction of the rotating field. The rotation of the field causes the lines of force to cut the cylinder and currents are induced in the copper. By Lenz's law (§ 499) the cylinder moves in the direction to check the induction in it; it is therefore dragged in the same direction as the rotation of the magnetic field. The cylinder tends to ro-

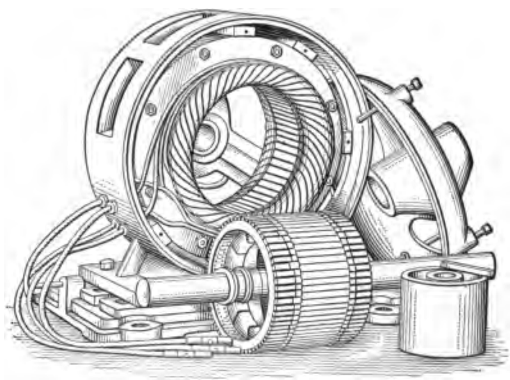


FIGURE 467. — INDUCTION MOTOR WITH "SQUIRREL CAGE" ROTOR.

tate as fast as the field, but never quite reaches it; for then there would be no cutting of lines of force and no induction. The difference in speed between the field and the *rotor*, as the cylinder is called, is known as the *slip*. If a little friction is applied to the cylinder, the slip will increase until the larger induced currents are just sufficient to supply the needed torque.

In commercial motors the actual rotor consists of a cylindrical core built up of thin steel disks, with slots or holes through parallel to the shaft. In these are embedded heavy copper rods or bars, which are joined together at

their ends, so as to form a "squirrel cage" of copper (Fig. 467). The induced currents flow in the rods. The rotor does not need to have either commutator or slip rings and is entirely separate from any other circuit. Its currents are wholly inductive. In some larger forms the rotor is wound like a drum armature, and the coils are connected through slip-rings, so that resistance may be inserted in the circuits at starting. This resistance is cut out as the motor gets up its speed.

III. ELECTRIC LIGHTING

542. The Carbon Arc. — In 1800 Sir Humphry Davy discovered that when two pieces of charcoal, suitably connected to a powerful voltaic battery, were brought into contact at their ends and were then separated a slight distance, brilliant sparks passed between them. No mention was made of the *electric arc* until 1808. With a battery of 2000 cells and the carbons in a horizontal line, they could be separated several inches, while the current was conducted across in the form of a curved flame or *arc*. Hence the name *electric arc* given to this form of electric lighting.

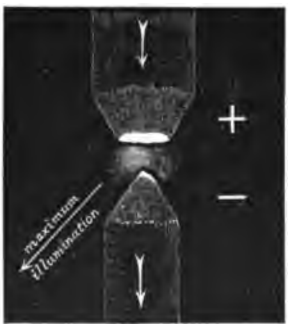


FIGURE 468. — THE ARC LIGHT, DIRECT CURRENT.

Dense compressed or molded carbon rods are now used, and when they are separated a slight distance they are heated to an exceedingly high temperature, and the current from a dynamo continues to pass across through the heated carbon vapor, which is ionized by the emission of electrons from the negative carbon.

The ends of the carbon rods in the open air are disintegrated, a depression or "crater" forming in the positive and a cone on the negative (Fig. 468). Most of the light of the open arc comes from the bottom of this crater, the temperature of which Violle has estimated to be 3500° C. The arc light may be produced in a vacuum. The intense heat is not, therefore, generated by combustion. It is the energy of the current converted into heat by the resistance of the arc. The usual current for arc lamps is from 5 to 10 amperes. For searchlights, arc lights of great power are produced by the use of thicker carbons and 100 or more amperes.

FIGURE 469. —THE INCLOSED ARC.

543. The Open and the Inclosed Arc. — To keep the carbon rods from burning away too rapidly, modern arc lamps are mostly of the "inclosed arc" type. The lower carbon and a part of the upper one are inclosed in a small glass globe, which is air-tight at the bottom, but allows the upper carbon to slip through a check-valve at the top (Fig. 469). Soon after the arc begins to burn, the oxygen in the globe is absorbed and the arc is then inclosed in an atmosphere of nitrogen from the air and of carbon monoxide from the incomplete combustion of the carbon. The inclosed arc is longer than the open arc, and the E.M.F. is about 80 volts instead of 50 as required by the open arc; but the current for the inclosed arc is smaller than for the open arc. The carbons for the inclosed arc last at least ten times as long as in the open air.

The direct current inclosed arc is operated at a higher temperature than the alternating current lamp, and is therefore more efficient.

544. Other Arc Lights. — Other arc lamps are now in commercial use in which the light comes chiefly from the incandescent stream between the electrodes. They have a higher efficiency than the carbon arc. In the *metallic arc* powdered *magnetite* in an iron tube is used for one electrode and a block of copper for the other. The arc flame is very white and brilliant, the light coming from the luminous iron vapor.

Flaming arcs are made by the use of a positive electrode impregnated with salts of calcium, chiefly calcium fluoride. The light from the flaming arc is yellow, and is adapted to outdoor illumination only.

The *mercury arc* of Cooper Hewitt is radically different from other arc lamps. It has the arc in a sealed tube, which is exhausted of air, and the light comes from luminous mercury vapor. It consists of a glass tube one inch in diameter and from 20 to 50 inches long, with a bulb at one end for holding mercury, and a small iron electrode at the other. A special device must be used to start the current. This light contains no red rays and thus gives a peculiar color to objects illuminated by it. This lamp operates by direct current only.

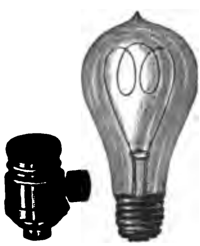


FIGURE 470. — CARBON FILAMENT LAMP.

545. Carbon Filament Lamps. — The principle of the incandescent lamp is the use of a filament or wire of such high resistance that it can be brought to glow by the passage of an electric current. The filament is inclosed in a glass bulb, exhausted of air, and has its ends connected through the glass by short pieces of platinum wire (Fig. 470). The carbon filament is now made from cellulose obtained from cotton.

The temperature to which a carbon filament can be raised is limited by the tendency of the carbon to vaporize at high temperatures. The carbon thrown off rapidly reduces the thickness of the filament and blackens the globe. The useful life of a carbon filament is from 500 to 700 hours.

The ordinary commercial unit for the carbon filament is the 16-candle power lamp. On a 110-volt circuit it takes about 0.5 ampere. Since the power in watts consumed is EI, this lamp requires about 55 watts, or 3.5 watts per candle. The efficiency of a lamp is expressed in watts per candle. The *efficiency* of the carbon filament lamp is from 3.1 to 3.5 watts per candle.

A metallized filament is obtained by heating a treated cellulose filament in an electric furnace to a very high temperature. It can be glowed at a higher temperature than the ordinary carbon filament; it has a corresponding higher efficiency of about 2.5 watts per candle for 50 and 60 watt lamps.

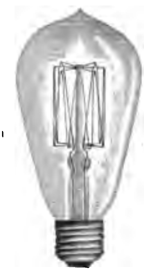


FIGURE 471.—TUNGSTEN FILAMENT LAMP.

546. Metal Filament Lamps. — Metal wires cannot be used in glow lamps unless their melting point is higher than that of platinum. The melting point of platinum is about 1775° and that of tungsten about 3200° C. The available metals for incandescent lamps are tantalum and tungsten. Their specific resistance is lower than that of carbon; hence filaments made of them must be longer and thinner than those of carbon. A piece of tungsten as large as a lead pencil contains enough material to make about five miles of wire for 40 watt lamps. A continuous tungsten filament is so long that it must be wound zigzag on a light frame or reel (Fig. 471). The tungsten 25 watt lamp gives 20 candle

power, or 1.25 watts per candle. By reason of its high efficiency it has largely displaced the carbon lamp, in spite of the fact that it is more fragile. The tungsten lamp has a useful life of from 800 to 1000 hours.

547. Gas-filled Lamps. — In many early lamp experiments the glass bulbs, after exhaustion of air, were filled with an inert gas. This practice was soon abandoned because the efficiency was lowered by the heat carried away from the filament to the bulb by convection in the gas. In recent developments it has been found that gas can be used to advantage with filaments of large cross-section in high power lamps. When the bulb of a lamp taking more than 75 watts is filled with an inert gas, like nitrogen or argon, it is possible to raise the temperature of the filament and in this way to get a higher efficiency. In thicker filaments the loss of heat by convection is more than offset by the gain secured by the use of a higher temperature. The twenty ampere series lamp, filled with argon, has an efficiency of half a watt per candle. In other words, a 500 watt lamp has a candle power of 1000. These lamps are specially adapted to the lighting of large areas and city streets (Fig. 472).

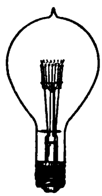


FIGURE 472. — GAS-FILLED LAMP.

548. Incandescent Lamp Circuits. — Incandescent lamps are connected in parallel between the mains in a building.

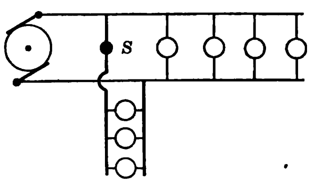


FIGURE 473. — INCANDESCENT LAMP CIRCUIT.

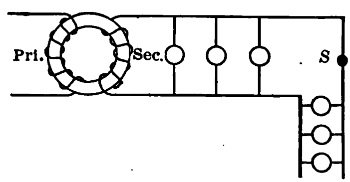


FIGURE 474. — LAMP CIRCUIT WITH TRANSFORMER.

These mains lead either directly to a dynamo (Fig. 473), or to the low voltage side of a transformer in the case of alternating currents (Fig. 474). Single lamps are turned off usually by the key in the socket (Fig. 470), and groups of lamps by a switch S (Fig. 474).

IV. THE ELECTRIC TELEGRAPH

549. The Electric Telegraph is a system of transmitting messages by means of simple signals through the agency of an electric current. Its essential parts are the *line*, the *transmitter* or *key*, the *receiver* or *sounder*, and the *battery*.

550. The Line is an iron, copper or phosphor-bronze wire, insulated from the earth except at its ends, and serving to connect the signaling apparatus. The ends of this conductor are connected with large metallic plates, or with gas or water pipes, buried in the earth. By this means the earth becomes a part of the electric circuit containing the signaling apparatus.

551. The Transmitter or Key (Fig. 475) is merely a current interrupter, and usually consists of a brass lever A, turning about pivots at B. It is connected with the line by the screws C and D. When the lever is pressed down, a platinum point projecting under the lever is brought in contact with another platinum point E, thus closing the circuit. When not in use, the circuit is left closed, the switch F being used for that purpose.

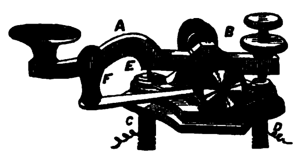


FIGURE 475. — TELEGRAPH KEY.

552. The Receiver or Sounder (Fig. 476) consists of an electromagnet A with a pivoted armature B. When the

circuit is closed through the terminals D and E, the armature is attracted to the magnet, producing a sharp click.

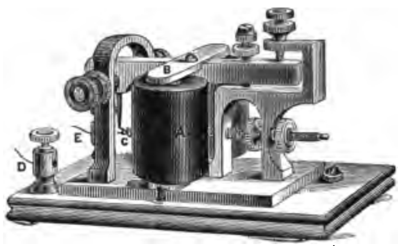


FIGURE 476.—TELEGRAPH SOUNDER.

When the circuit is broken, a spring C causes the lever to rise and strike the backstop with a lighter click.

553. The Relay.—When the resistance of the line is large, the current is not likely to be strong enough to operate the sounder with sufficient energy to render the signals distinctly audible. To remedy this defect, an electromagnet, called a *relay* (Fig. 477), whose helix A is composed of many turns of fine wire, is placed in the circuit by means of its terminals C and D. As its armature moves to and fro between points, it opens and closes a shorter local circuit through E and F, in which the sounder is placed. Thus the weak current, through the agency of the relay, brings into action a current strong enough to work the local sounder with a loud click.

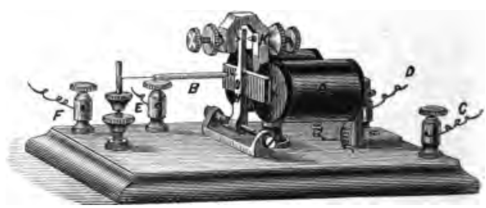


FIGURE 477.—TELEGRAPH RELAY.

554. The Battery consists of a large number of cells, usually of the gravity type, connected in series. It is generally divided into two sections, one placed at each terminal station, these sections being connected in series through the line. The principal circuits of the great

Alexander Graham Bell was born in Edinburgh, Scotland, in 1847. His father, Alexander Melville Bell, was a teacher and inventor. The son came to the United States in 1872 and became professor at Boston University. While there he invented the telephone in 1875. He also invented the photophone, and developed his father's system of phonetics.

Samuel F. B. Morse (1791–1872) was born at Charlestown, Massachusetts, and died in New York City. After graduating from Yale at the age of nineteen, he studied art in England under Benjamin West. In 1832 he perfected the electric telegraph, and in 1843 was granted an appropriation by Congress for a line between Washington and Baltimore. In 1844 this line was completed, — the first successful electric telegraph on a large scale.

telegraph companies are now worked by means of currents from dynamo machines.

555. The Signals are a series of sharp and light clicks separated by intervals of silence of greater or less duration, a short interval between the clicks being known as a "dot," and a long one as a "dash." By a combination of "dots" and "dashes," letters are represented and words are spelled out.

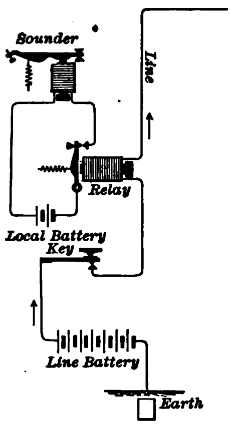


FIGURE 478. — TERMINAL INSTRUMENTS ON TELEGRAPH LINE.

556. The Telegraph System described in the preceding sections is known as Morse's, from its inventor. Figure 478 illustrates diagrammatically the instruments necessary for one terminal station, together with the mode of connection. The arrangement at the other end of the line is an exact duplicate of this one, the two sections of the battery being placed in the line, so that the negative pole of one and the positive pole of the other are connected with the earth. At intermediate stations the relay and the local circuit are connected with the line in the same manner as at a terminal station.

FIGURE 479. — ELECTRIC BELL.

557. The Electric Bell (Fig. 479) is used for sending signals as distinguished from messages. Besides the gong, it contains an electromagnet, having one terminal connected directly with a binding-post, and

the other through a light spring attached to the armature (shown on the left of the figure) and a contact screw, with another binding-post. One end of the armature is supported by a stout spring, or on pivots, and the other carries the bent arm and hammer to strike the bell. Included in the circuit are a battery and a push-button *B*, shown with the top unscrewed in Fig. 480.

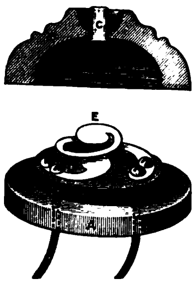


FIGURE 480. — PUSH-BUTTON.

When the spring *E* is brought into contact with *D* by pushing *C*, the circuit is closed, the electromagnet attracts the armature, and the hammer strikes the gong. The movement of the armature opens the circuit by breaking contact between the spring and the point of the screw; the armature is then released, the retractile spring at the bottom carries it back, and contact is again established between the spring and the screw. The whole operation is repeated automatically as long as the circuit is kept closed at the push-button. A "buzzer" is an electric bell without the hammer and gong.

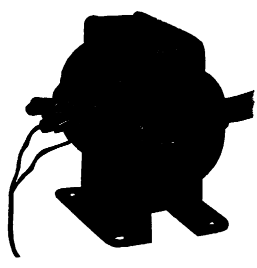


FIGURE 481. — TRANSFORMER FOR RINGING BELLS.

Instead of two dry cells for ringing house bells, a small step-down transformer connected to the lighting wires, with the bells in circuit on the low voltage side, gives satisfactory service (Fig. 481). The bells need not be changed in any way, since the frequency of the current is too high to permit them to respond without the usual automatic circuit breaker.

V. THE TELEPHONE

558. The Telephone (Fig. 482) consists of a horseshoe magnet *O*, both poles of which are surrounded by a coil of many turns of fine copper wire whose ends are connected with the binding-posts *t* and *t*. At right angles to the magnet, and not quite touching the poles, within the coils, is an elastic diaphragm or disk of soft sheet-iron, kept in place by the conical mouthpiece *d*. If the instrument is placed in an electric circuit when the current is unsteady, or alternating in direction, the magnetic field due to the helix, when combined with that due to the magnet, alters intermittently the number of lines of force which branch out from the poles, thus varying the attraction of the magnet for the disk. The result is that the disk vibrates in exact keeping with the changes in the current.

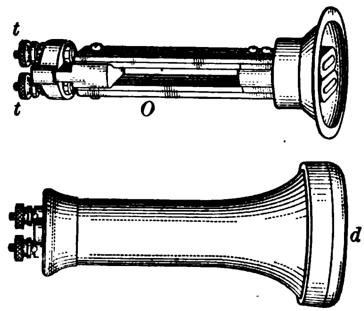


FIGURE 482. — THE MODERN TELEPHONE.

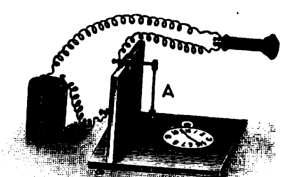


FIGURE 483. — MICROPHONE.

559. The Microphone is a device for varying an electric current by means of a variable resistance in the circuit. One of its simplest forms is shown in Figure 483. It consists of a rod of gas-carbon *A*, whose tapering ends rest loosely in conical depressions made in blocks of the same material attached to a sounding board. These blocks are placed in circuit with a

battery and a telephone. While the current is passing, the least motion of the sounding board, caused either by sound waves or by any other means, such as the ticking of a watch, moves the loose carbon pencil and varies the pressure between its ends and the supporting bars. A slight increase of pressure between two conductors, resting loosely one on the other, lessens the resistance of the contact, and conversely. Hence, the vibrations of the sounding board cause variations in the pressure at the points of contact of the carbons, and consequently make corresponding fluctuations in the current and vibrations of the telephone disk.

560. The Solid Back Transmitter.—The varying resistance of carbon under varying pressure makes it a valuable material for use in telephone transmitters. Instead of the loose contact of the microphone, carbon in granules between carbon plates is now commonly employed.

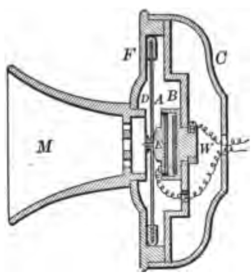


FIGURE 484. — SOLID BACK TRANSMITTER.

The form of transmitter extensively used for long distance work is the "solid back" transmitter (Fig. 484). The figure shows only the essential parts in section, minor details being omitted. *M* is the mouthpiece, and *F* and *C* the front and back parts of the metal case. The aluminum diaphragm *D* is held around its edge by a soft rubber ring. The metal block *W* has a recess in front to receive the carbon electrodes *A* and *B*. Between them are the carbon granules. The block *E* is attached to the diaphragm and is insulated from *W* except through the carbon granules. The transmitter is placed in circuit by the wires connected to *W* and *E*.

Provision is made for an elastic motion of the diaphragm and the block *E*. Sound waves striking the diaphragm cause a varying pressure between the plates and the carbon granules. This varying pressure varies the resistance offered by the granules and so varies the current. The transmitter is in circuit in the line with the primary of a small induction coil, the secondary being in a local circuit with the telephone receiver. The induced currents in the secondary have all the peculiarities of the primary current; and when they pass through a receiver, it responds and reproduces sound waves similar to those which disturb the disk of the transmitter.

VI. WIRELESS TELEGRAPHY

561. Oscillatory Discharges. — The discharge of any condenser through a circuit of low resistance is oscillatory. The first rush of the discharge surges beyond the condition of equilibrium, and the condenser is charged in the opposite sense. A reverse discharge follows, and so on, each successive pulse being weaker than the preceding, until after a few surges the oscillations cease. Figure 485 was made from a photograph of the oscillatory discharge of a condenser by means of a very small mirror, which reflected a beam of light on a falling sensitized plate. Such alternating surges of high frequency are called *electric oscillations*. Joseph Henry discovered long ago that the discharge of a Leyden jar is oscillatory.

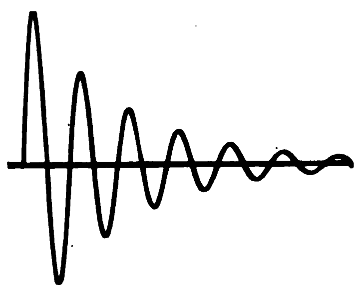


FIGURE 485. — OSCILLATORY DISCHARGE.

562. Electric Waves. — In 1887–1888 Hertz made the discovery that electric oscillations give rise to electric waves in the ether, know as Hertzian waves, which appear to be the same as waves of light, except that they are very much longer, or of lower frequency. They are capable of reflection, refraction, and polarization the same as light.

Evidence of these waves may be readily obtained by setting up an induction coil, with two sheets of tin-foil on glass, Q and Q', connected with the terminals of the sec-

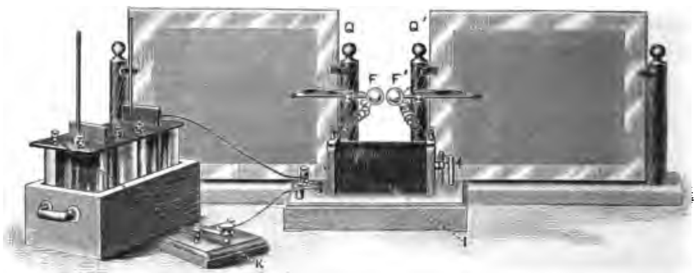


FIGURE 486. — ELECTRIC WAVE TRANSMITTER.

ondary coil, and with two discharge balls, F and F', as shown in Fig. 486. So simple a device as a large picture frame with a conducting gilt border may be used to detect waves from the tin-foil sheets. If the frame has shrunken so as to leave narrow gaps in the miter at the corners, minute sparks may be seen in a dark room breaking across these gaps when the induction coil produces vivid sparks between the polished balls, F and F'. The plane of the frame should be held parallel with the sheets of tin-foil. The passage of electric waves through a conducting circuit produces electric oscillations in it, and these oscillations cause electric surges across a minute air gap.

Heinrich Rudolf Hertz (1857–1894) was born in Hamburg, and was educated for a civil engineer. Having decided to abandon his profession, he went to Berlin and studied under Helmholtz, and later became his assistant. In 1885 he was appointed professor of physics at the Technical High School at Karlsruhe, and while there he discovered the electromagnetic waves predicted by Maxwell, who in the middle of the century had advanced the idea that waves of light are electromagnetic in character. In 1889 he was elected professor of physics at Bonn, where he died at the age of thirty-seven. Electromagnetic waves are called Hertzian waves in his honor.

563. The Coherer. — One of the earliest devices for the detection of electric waves is the *coherer* (Fig. 487). When metal filings are placed loosely between solid electrodes in a glass tube they offer a high resistance to the passage of an electric current; but when electric oscillations are produced in the neighborhood of the tube, the resistance of the filings falls to so small a value that a single voltaic cell sends through them a current strong enough to work a relay (§ 553). If the tube is slightly jarred, the filings resume their state of high resistance. A minute discharge from the cover of an electrophorus (§ 432) through the filings lowers the resistance just as electric oscillations do. It is thought that minute sparks between the filings partially weld them together and make them conducting.

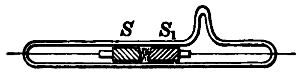


FIGURE 487. — THE COHERER.

564. Crystal Detectors. — The coherer is now obsolete and more sensitive detectors have been discovered. The object aimed at in most of them is the rectification of the rapid oscillations from the receiving antenna or aërial wire, so as to secure a unidirectional discharge which will affect a telephone. On account of its high self-inductance, a telephone acts as a choke coil to high frequency electric oscillations and will not respond to them. It has been found that certain crystals, such as polished silicon, galena, and carborundum, possess a unilateral conductivity for electricity. A crystal of carborundum may have three or four thousand times as great conductivity in one direction as in the opposite for certain voltages. Hence, if a crystal detector is inserted in the oscillation circuit of a receiver, it rectifies the oscillations in a train of electric impulses, to which a telephone will respond with a sound corresponding in pitch to the number of impulses per second.

The crystal is held in a conducting holder and is touched lightly by a metal point (Fig. 488). The brass cup shown in the figure holds the crystal securely by means of three set screws. Another method of mounting is to embed the crystal in a soft alloy which melts at a low temperature. The contact wire can be moved about so as to find the sensitive spots in the crystal.

FIGURE 488. — HOLDER FOR CRYSTAL DETECTOR.

565. The Audion is a very sensitive detector, depending for its action on the fact that electrons are thrown off from the *negative* end of an incandescent filament in an exhausted (or partly exhausted) bulb. If the bulb has supported in it a plate surrounding the filament (Fig. 489), a single voltaic cell will send a (negative) current from its *negative* electrode to the *negative* end of the hot filament, thence through the space in the bulb to the metal plate, and out to the other pole of the voltaic cell. No current will flow unless the *negative* pole of the cell is connected to the *negative* of the filament. This arrangement is therefore an electric valve or rectifier, which lets electric impulses through in one direction and not in the other. Fleming calls it an "oscillation valve." In the figure, oscillations in one direction from the oscillation transformer *T* will pass through the circuit, including the valve *V* and the telephone *P*, but not those in the other direction.

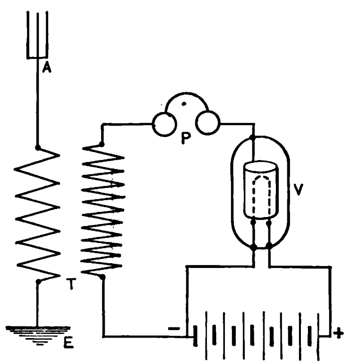


FIGURE 489. — "OSCILLATION VALVE."

The *audion* is a modification of the "oscillation valve" of Fleming, which becomes a relay for the aërial oscillations to operate receiving

telephones in a circuit with a battery (Fig. 490). In addition to the hot filament and the metal plate the audion has a "grid" consisting of a coil of copper wire, which is one terminal of the circuit from the receiving helix. The other terminal of this circuit is joined to the filament. The negative of the adjustable battery *B* is joined to the negative end of the filament. The rectified train of impulses passes through from the hot filament to the copper coil. *The passage of these impulses causes similar impulses from the battery B to pass between the filament and the metal plate*, and hence through the receiving telephone *T*.

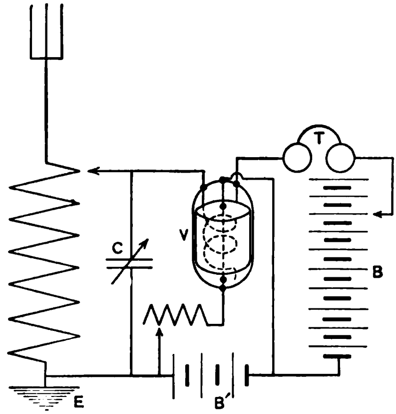


FIGURE 490.—THE AUDION.

566. Transmitting and Receiving Circuits. — A simple tuned transmitting circuit for wireless telegraphy is illustrated in Figure 491, where *I* is an induction coil, *C* a condenser, *S* a spark gap, *H* a variable helix, *A* the aërial or antenna, and *E* the earth connection.

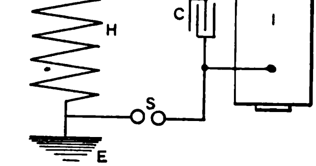


FIGURE 491.—TRANSMITTING CIRCUIT.

Figure 492 is a corresponding simple receiving circuit. The receiving telephones are shown at *T*, the detector at *D*, and a variable condenser at *C*. These arrangements are capable of many variations.

The magnetic effect of a rectified train of electric impulses is never reversed. Hence they pass through the

high resistance telephones and produce a distinct musical tone. Continued tones are interpreted as dashes and short ones as dots; together they make up either the Morse or the Continental alphabet.

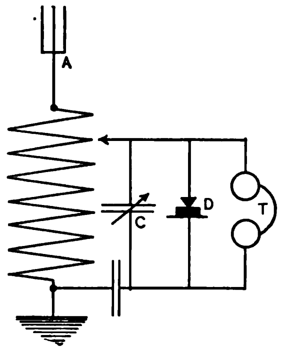


FIGURE 492. — RECEIVING CIRCUIT.

The circuits in commercial wireless telegraphy are much more elaborate than those shown (Fig. 493). To avoid interference between signals from different stations, it is necessary to tune the sending and receiving circuits to the same frequency. They are then sensitive to one frequency and not to others. For detailed information the reader is advised to consult technical books on wireless telegraphy.

567. Uses of Wireless Telegraphy. — In less than thirty years after Hertz's fundamental discovery, wireless telegraphy has grown to large proportions, especially for signals between ships at sea and for international intercourse. Wireless telegraphy is in use between all steamships. They are thus in communication with one another and with stations on the land. Various government stations have been erected for the purpose of keeping each government in communication with the ships in its navy, and with other governments. Notable among these are the station in Paris, for which the Eiffel Tower is utilized to support the antenna, and the station in Arlington near Washington. Communication between these two stations is not difficult, and signals between them have been used to determine the difference of longitude between Paris and Washington. During the progress of this work, the

Thomas Alva Edison was born at Milan, Ohio, in 1847. Beginning life as a newsboy, he has become the greatest American inventor. He perfected duplex telegraphy, and invented among other things the carbon telephone transmitter, the microtasimeter, the aërophone, the megaphone, the phonograph, the kinetoscope, and the incandescent electric lamp.

Guglielmo Marconi was born at Bologna, Italy, in 1874. He studied in his native city, at Leghorn, and also, for a short time, in England. At the age of twenty-one he began his experiments in wireless telegraphy, and by 1895 was able to send messages across the English Channel. Since then his system has been so developed that marconigrams are sent across the Atlantic, and practically all important ships are equipped with wireless apparatus.

time of transmission of the signals between Paris and Washington was found to be 0.021 second. Signals are occasionally received at the Marconi Station, County Galway, Ireland, from stations many thousand miles away; for example, from Darien, San Francisco, and Honolulu.

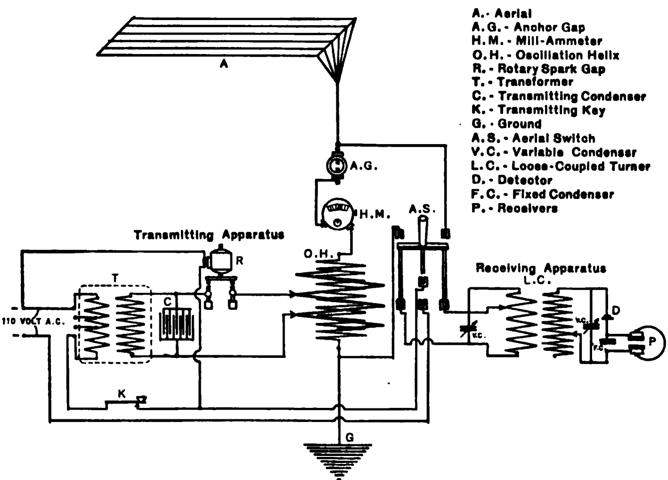


FIGURE 493. — COMMERCIAL TRANSMITTING AND RECEIVING APPARATUS.

568. Wireless Telephony. — For the purpose of transmitting speech by wireless, it is necessary to have a source of energy that will transmit a persistent train of undamped waves. This may be accomplished either by means of an oscillating arc or by a high frequency alternator. These must emit continuous trains of waves with a frequency of 4000 or more per second. A special microphone carves the transmitted current and the train of waves emitted into groups of amplitudes corresponding with the sounds spoken into the microphone. The words are received with the usual telephonic receivers.

APPENDIX

I. GEOMETRICAL CONSTRUCTIONS

The principal instruments required for the accurate construction of diagrams on paper are the *compasses* and the *ruler*. For the construction of angles of any definite size the *protractor* (Fig. 494) can be used. There are, however, a number of angles, as 90°, 60°, and those which can be obtained from these by bisecting them and combining their parts, that can be constructed by the compasses and ruler alone.

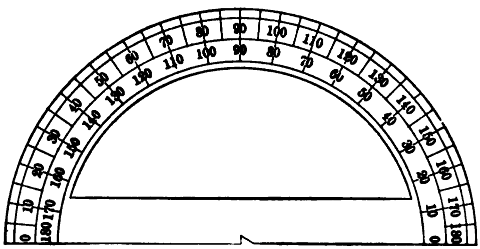


FIGURE 494.

A convenient instrument for the rapid construction of the angles 90°, 60°, and 30°, is a triangle made of wood, horn, hard rubber, or cardboard, whose angles are these respectively. Such a triangle may be easily made from a postal card as follows: Lay off on the short side of the card (Fig. 495) a distance a little less than the width, as *AB*. Separate the points of the compasses a distance equal to twice this distance. Place one point of the compasses at *B*, and draw an arc cutting the adjacent side at *C*.

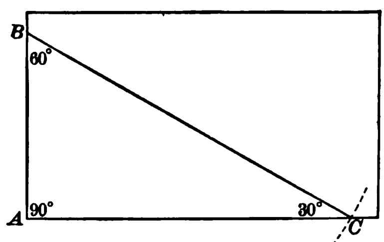


FIGURE 495.

Cut the card into two parts along the straight line BC. The part ABC will be a right-angled triangle, having the longest side twice as long as the shortest side, with the larger acute angle 60° and the smaller 30°. With this triangle and a straight edge the majority of the constructions required in elementary physics can be made.

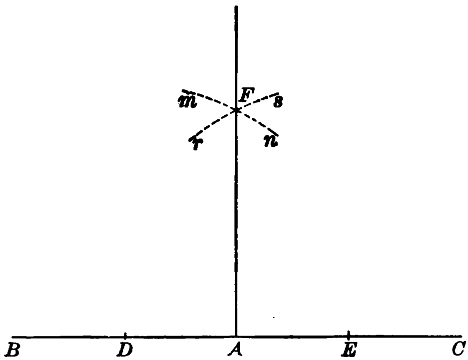


FIGURE 496.

PROB. 1. — *To construct an angle of 90°.*

Let A be the vertex of the required angle (Fig. 496). Through A draw the straight line BC. Measure off AD, any convenient distance; also make $AE = AD$. With a pair of compasses, using D as a center, and a radius longer than AD, draw the arc mn; with E as a center and the same radius, draw the arc rs, intersecting mn at F. Join A and F. The angles at A are right angles.

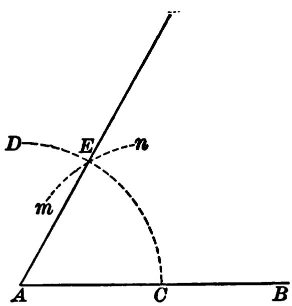


FIGURE 497.

PROB. 2. — *To construct an angle of 60°.*

Let A be the vertex of the required angle (Fig. 497), and AB one of the sides. On AB take some convenient distance as AC. With a pair of compasses, using A as a center and AC as a radius, draw the arc CD. With C as a center and the same radius, draw the arc mn, intersecting CD at E. Through A and E draw the straight line AE; this line will make an angle of 60° with AB.

Prob. 3. — *To bisect an angle.*

Let BAC be an angle that it is required to bisect (Fig. 498). Measure off on the sides of the angle equal distances, AD and AE. With D and E as centers and with the same radius, draw the arcs mn and rs, intersecting at F. Draw AF. This line will bisect the angle BAC.

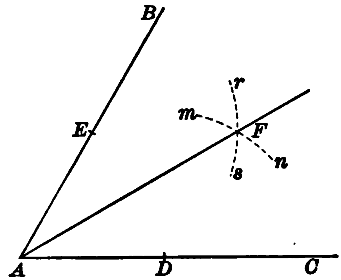


FIGURE 498.

Prob. 4. — *To make an angle equal to given angle.*

Let BAC be a given angle; it is required to make a second angle equal to it (Fig. 499). Draw DE, one side of the required angle. With A as a center and any convenient radius, draw the arc mn across the given angle. With D as a center and the same radius, draw the arc rs. With s as a center and a radius equal to the chord of

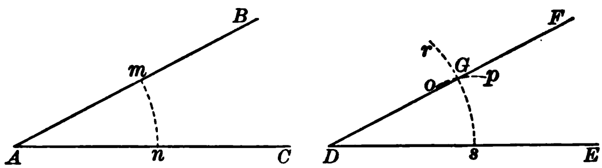


FIGURE 499.

mn, draw the arc op, cutting rs at G. Through D and G draw the line DF. This line will form with DE the required angle, as FDE.

Prob. 5. — *To draw a line through a point parallel to a given line.*

Let A be the point through which it is required to draw a line parallel to BC (Fig. 500). Through A draw ED,

cutting *BC* at *D*. At *A* make the angle *EAG* equal to *EDC*. Then *AG* or *FG* is parallel to *BC*.

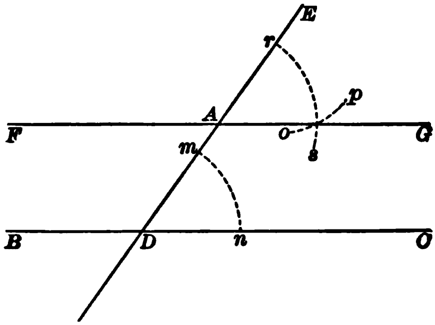


FIGURE 500.

PROB. 6. — *Given two adjacent sides of a parallelogram to complete the figure.*

Let *AB* and *AC* be two adjacent sides of the parallelogram (Fig. 501). With *C* as a center and a radius equal to *AB*,

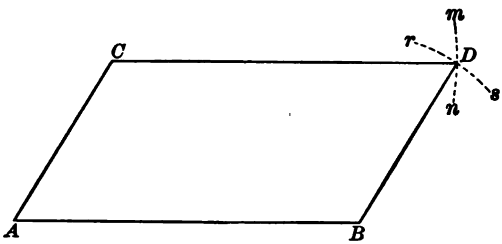


FIGURE 501.

draw the arc *mn*. With *B* as a center and a radius equal to *AC*, draw the arc *rs*, cutting *mn* at *D*. Draw *CD* and *BD*. Then *ABDC* is the required parallelogram.

II. CONVERSION TABLES

1. Length

To reduce	Multiply by	To reduce	Multiply by
Miles to km.	1.60935	Kilometers to mi.	0.62137
Miles to m.	1609.347	Meters to mi.	0.0006214
Yards to m.	0.91440	Meters to yd.	1.09361
Feet to m.	0.30480	Meters to ft.	3.28083
Inches to cm.	2.54000	Centimeters to in.	0.39370
Inches to mm.	25.40005	Millimeters to in.	0.03937

2. Surface

To reduce	Multiply by	To reduce	Multiply by
Sq. yards to $m.^2$	0.83613	Sq. meters to sq. yd.	1.19599
Sq. feet to $m.^2$	0.09290	Sq. meters to sq. ft.	10.76387
Sq. inches to $cm.^2$	6.45163	Sq. centimeters to sq. in.	0.15500
Sq. inches to $mm.^2$	645.163	Sq. millimeters to sq. in.	0.00155

3. Volume

To reduce	Multiply by	To reduce	Multiply by
Cu. yards to $m.^3$	0.76456	Cu. meters to cu. yd.	1.30802
Cu. feet to $m.^3$	0.02832	Cu. meters to cu. ft.	35.31661
Cu. inches to $cm.^3$	16.38716	Cu. centimeters to cu. in.	0.06102
Cu. feet to liters	28.31701	Liters to cu. ft.	0.03532
Cu. inches to liters	0.01639	Liters to cu. in.	61.02337
Gallons to liters	3.78543	Liters to gallons	0.26417
Pounds of water to liters	0.45359	Liters of water to lb.	2.20462

4. Weight

To reduce	Multiply by	To reduce	Multiply by
Tons to kg.	907.18486	Kilograms to tons	0.001102
Pounds to kg.	0.45359	Kilograms to lb.	2.20462
Ounces to g.	28.34953	Grams to oz.	0.03527
Grains to g.	0.064799	Grams to grains	15.43236

5. Force, Work, Activity, Pressure

To reduce	Multiply by	To reduce	Multiply by
Lb.-weight to dynes, .	444520.58	Dynes to lb.-weight,	22496×10^{-10}
Ft.-lb. to kg.-m.	0.138255	Kg.-m. to ft.-lb. . . .	7.233
Ft.-lb. to ergs . . .	13549×10^{8}	Ergs to ft.-lb. . .	0.7381×10^{-7}
Ft.-lb. to joules . .	1.3549	Joules to ft.-lb. . . .	0.7381
Ft.-lb. per sec. to H.P.	18182×10^{-7}	H.P. to ft.-lb. per sec. .	550
H.P. to watts	745.196	Watts to H.P.	0.001342
Lb. per sq. ft. to kg. per m.^{2}	4.8824	Kg. per m.^{2} to lb. per sq. ft.	0.2048
Lb. per sq. in. to g. per cm.^{2}	70.3068	G. per cm.^{2} to lb. per sq. in.	0.01422

Calculated for $g = 980$ cm., or 32.15 ft.-per-sec. per sec.

6. Miscellaneous

To reduce	Multiply by	To reduce	Multiply by
Lb. of water to U.S. gal.	0.11983	U.S. gal. to lb. of water.	8.345
Cu. ft. to U.S. gal. . . .	7.48052	U.S. gal. to cu. ft. . .	0.13368
Lb. of water to cu. ft. at 4° C.	0.01602	Cu. ft. of water at 4° C. to lb.	62.425
Cu. in. to U.S. gal. . . .	0.004329	U.S. gal. to cu. in. . .	231
Atmospheres to lb. per sq. in.	14.69640	Lb. per sq. in. to atmospheres	0.06737
Atmospheres to g. per cm.^{2}	1033.296	G. per cm.^{2} to atmospheres	0.000968
Lb.-degrees F. to calories.	252	Calories to lb.-degrees F.	0.003968
Calories to joules . . .	4.18936	Joules to calories . . .	0.2387
Miles per hour to ft. per sec.	1.46667	Ft. per sec. to miles per hour	0.68182
Miles per hour to cm. per sec.	44.704	Cm. per sec. to miles per hour	0.02237

III. MENSURATION RULES

Area of triangle	$= \frac{1}{2}$ (base × altitude).
Area of triangle	$= \sqrt{s(s-a)(s-b)(s-c)}$ where $s = \frac{1}{2}(a+b+c)$.
Area of parallelogram	= base × altitude.
Area of trapezoid	= Altitude × $\frac{1}{2}$ sum of parallel sides.
Circumference of circle	= diameter × 3.1416.
Diameter of circle	= circumference ÷ 3.1416. = circumference × 0.3183.
Area of circle	= diameter squared × 0.7854. = radius squared × 3.1416.
Area of ellipse	= product of diameters × 0.7854.
Area of regular polygon	$= \frac{1}{2}$ (sum of sides × apothem).
Lateral surface of cylinder	= circumference of base × altitude.
Volume of cylinder	= area of base × altitude.
Surface of sphere	= diameter × circumference. = 4 × 3.1416 × square of radius.
Volume of sphere	= diameter cubed × 0.5236. = $\frac{4}{3}$ of radius cubed × 3.1416.
Surface of pyramid Surface of cone	$= \frac{1}{2}$ (circumference of base × slant height).
Volume of cone	$= \frac{1}{3}$ (area of base × altitude).

IV. TABLE OF DENSITIES

The following table gives the mass in grams of 1 $cm.^3$ of the substance: —

Agate	2.615	Human body	0.890
Air, at 0° C. and 76 cm. pressure	0.00129	Hydrogen, at 0° C. and 76 cm. pressure	0.0000896
Alcohol, ethyl, 90%, 20° C.	0.818	Ice	0.917
Alcohol, methyl	0.814	Iceland spar	2.723
Alum, common	1.724	India rubber	0.930
Aluminum, wrought	2.670	Iron, white cast	7.655
Antimony, cast	6.720	Iron, wrought	7.698
Beeswax	0.964	Ivory	1.820
Bismuth, cast	9.822	Lead, cast	11.360
Brass, cast	8.400	Magnesium	1.750
Brass, hard drawn	8.700	Marble	2.720
Carbon, gas	1.89	Mercury, at 0° C.	13.596
Carbon disulphide	1.293	Mercury, at 20° C.	13.558
Charcoal	1.6	Milk	1.032
Coal, anthracite	1.26 to 1.800	Nitrogen, at 0° C. and 76 cm. pressure	0.001255
Coal, bituminous	1.27 to 1.423	Oil, olive	0.915
Copper, cast	8.830	Oxygen, at 0° C. and 76 cm. pressure	0.00143
Copper, sheet	8.878	Paraffin	0.824 to 0.940
Cork	0.14 to 0.24	Platinum	21.531
Diamond	3.530	Potassium	0.865
Ebony	1.187	Silver, wrought	10.56
Emery	3.900	Sodium	0.970
Ether	0.736	Steel	7.816
Galena	7.580	Sulphuric Acid	1.84
German silver	8.432	Sulphur	2.033
Glass, crown	2.520	Sugar, cane	1.593
Glass, flint	3.0 to 3.600	Tin, cast	7.290
Glass, plate	2.760	Water, at 0° C.	0.999
Glycerin	1.260	Water, at 20° C.	0.998
Gold	19.360	Water, sea	1.027
Granite	2.650	Zinc, cast	7.000
Graphite	2.500		
Gypsum, crys.	2.310		

V. GEOMETRICAL CONSTRUCTION FOR REFRACTION OF LIGHT

The path of a ray of light in passing from one medium into another of different optical density is easily constructed geometrically. The following problems will make the process clear:

First.—A ray from air into water.—Let MN (Fig. 502) be the surface separating air from water, AB the incident ray at B, and BE the normal. With B as a center and a radius BA draw the arcs mn and Cs. With the same center and a radius $\frac{3}{4}$ of AB, ($\frac{4}{3}$ being the index for air to water), draw the arc Dr. Produce AB till it cuts the inner arc at D. Through D draw DC parallel to the normal EF, cutting the outer arc at C. Draw BC. This will be the refracted ray, because $\frac{AE}{CF} = \frac{4}{3}$, the index of refraction.

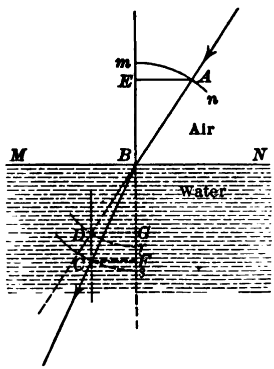


FIGURE 502.

When the ray passes from a medium into one of less optical density, then the ray is produced until it cuts the outer or arc of larger radius, and a line is drawn through this point parallel to the normal. The intersection of this line with the inner arc gives a point in the refracted ray which together with the point of incidence locates the ray.

If the incident angle is such that this line drawn parallel to the normal does not cut the inner arc, then the ray does not pass into the medium at that point but is totally reflected as from a mirror.

It is immaterial whether the arcs Dr and Cs are drawn in the quadrant from which the light proceeds, or, as in the figure, in the quadrant toward which it is going.

Second.— Tracing a ray through a lens.—Let MN represent a lens whose centers of curvature are C and C', and AB the ray to be traced through it (Figs. 503, 504). Draw the normal,

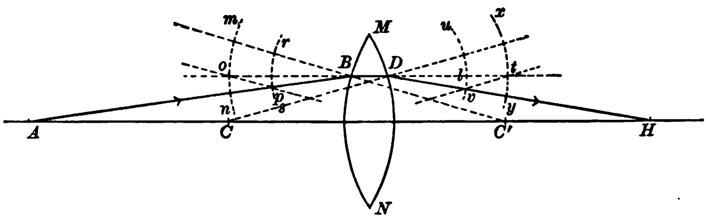


FIGURE 503.

$C'B$, to the point of incidence. With B as a center, draw the arcs mn and rs, making the ratio of their radii equal the index of refraction, $\frac{3}{2}$. Through p, the intersection of AB with rs, draw op parallel to the normal, $C'B$, and cutting mn at o. Through o and B draw oBD; this will be the path of the ray through the lens. At D it will again be refracted; to determine the amount, draw the normal CD and the auxiliary circles, xy and uv, as before. Through the intersection of BD produced with xy, draw lt parallel to the normal CD, cutting uv at l. Through D and l draw DH; this will be the path of the ray after emergence.

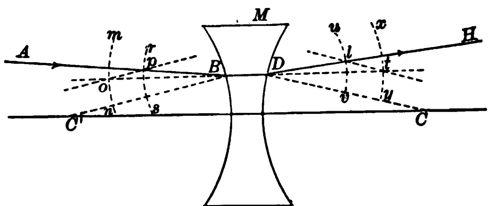


FIGURE 504.

When the index of refraction is $\frac{3}{2}$, the principal focus of both the double convex and the double concave lens is at the center of curvature; for plano-lenses, it is at twice the radius of curvature from the lens.

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First Year Science

By WILLIAM H. SNYDER, Principal of the Hollywood High School, Los Angeles, California. 12mo, cloth, 493 pages. Price, $1.25.

FIRST Year Science deals with the earth and the sun in their relations to man. In connection with these relations the various sciences are studied. Thus the book has a unity which is not found in many of the text-books in first year science.

First Year Science is meant for immature students. The language is simple, not technical, and the principles are throughout illustrated by specific examples of their occurrence and by pictures and experiments. As the author recognizes that too terse a treatment tends to confuse young students, the topics are sufficiently discussed to enable young pupils to master them with ease.

All the subjects of elementary school science — physics, chemistry, meteorology, botany, zoölogy, physiology, astronomy, physiography, forestry, and agriculture — are treated, so that the pupil can find out for himself which ones he wishes to study later in the course.

This text-book is complete in itself; no reference library, no manual, is needed. The experiments require only the simplest apparatus. In most cases, the mere reading of them is sufficient to illustrate the text.

The book is thoroughly equipped with summaries and questions at the end of each chapter.

It is felt that the chief reason for studying science in the first year is to make the subject attractive to young pupils, so that they will pursue the study further. For this reason no pains have been spared to make the book interesting and attractive. A large amount of time is spent on the treatment of big subjects, which take easy hold of the youthful imagination, such as the Earth and the Planets, the Ocean, Mountains, Volcanoes, and Glaciers. In connection with these the various specialized sciences are given adequate treatment.

The book is beautifully illustrated with over four hundred pictures and more than twenty maps.

A Laboratory Guide to accompany Carhart and Chute's Physics with Applications

By H. N. CHUTE, of the High School, Ann Arbor, Michigan. 12mo, flexible cloth, 127 pages. Price, 50 cents.

IN this Manual the author has chosen such problems as his experience has shown to be within the range of the beginner's skill.

There are seventy experiments: (1) those interesting boys and girls alike in the study of physics, (2) those requiring apparatus so simple as to be easily provided, and (3) those illustrating the methods of modern physics. Special attention is devoted to the preparation of the note-book, and for this purpose an unusual array of excellent illustrations is given in the text.

Laboratory Exercises in Physics

By ROBERT W. FULLER and RAYMOND B. BROWNLEE, Stuyvesant High School, New York City. 12mo, cloth, 324 pages. Price, 75 cents.

THIS Laboratory Manual is intended primarily to accompany *Carhart and Chute's Physics with Applications*, which it follows in the order of subjects. It is so arranged, however, that it can be used with any modern text-book in Physics.

There are ninety experiments in the book. These cover a field so wide that from them may be selected a thorough course which can be given with the apparatus found in any school. At the same time the book affords enough material to satisfy teachers who have the best-equipped laboratories at their disposal.

While the experiments meet the requirements of the College Entrance Board, particular effort has been made to adapt the work to the needs of pupils *not* preparing for college.

The directions are simple and clear, and adapted to the ability of beginners in Physics. There are full instructions on the making of note-books.

First Principles of Chemistry: Revised Edition

By RAYMOND B. BROWNLEE, Stuyvesant High School; ROBERT W. FULLER, Stuyvesant High School; WILLIAM J. HANCOCK, Erasmus Hall High School; MICHAEL D. SOHON, Morris High School; and JESSE E. WHITSIT, De Witt Clinton High School; all of New York City. 12mo, cloth, 535 pages. Price, $1.25.

THE revised edition of First Principles of Chemistry follows the general plan of the original book, but many important changes have been made in details.

The entire text has been carefully worked over with the idea of making all statements as simple and lucid as possible. The book has been brought up to date in regard to new developments in science.

Chapters on Chemical Equilibrium and Radioactivity have been added, to introduce the student to these important developments in chemistry. The chapters on Chemical Calculation and on The Compounds of Carbon have been largely rewritten.

The descriptions of chemical manufacturing processes have been brought up to date, and a number of commercial applications of chemistry have been added in the present book.

Added human interest is given to the book by new portraits and biographies of eminent chemists, many of them Americans.

The book was prepared by the committee of teachers that was called upon to frame the Syllabus in Chemistry for New York State. In selecting their material, the authors were governed wholly by what they considered its intrinsic value to the elementary student, regardless of its traditional place in a text-book.

The experimental evidence precedes the chemical theory. The historical order is followed as far as possible in developing the theory. The practical aspects of the science are emphasized.

The authors have made a special effort to give some idea of the great commercial importance of chemistry.

An important feature of the book is the brief summary and the test exercises given at the end of each chapter.

The LABORATORY MANUAL to accompany First Principles of Chemistry is described on page 73.

Text-Book of Cooking for Secondary Schools

By CARLOTTA C. GREER, East Technical High School, Cleveland.
12mo, cloth, 447 page. Price, $ 1.25.

THIS is not a book of recipes — it is literally a *Text-Book of Practical Cooking*, with a logically developed Study of Foods. The methods of work are the outgrowth of practical experience, and the book reveals the scientific principles on which these methods are based. Statements involving applied sciences have been carefully kept within the understanding of high school pupils.

The Text-Book is divided into two parts. Part I treats of "The Cooking of Foods," Part II of "Planning and Serving of Meals and the Calculation of the Food Value of Meals."

Part I is designed to teach pupils to select and to cook foods. It is also a study of their composition and their uses in the body. The pupils follow established recipes and are taught to consider the processes of cooking as experiments in a scientific study.

Added to recipes and directions are suggestions that assist the pupil to appreciate the significance of each step he takes.

In the reviews the pupil is helped to work out his own scheme for preparing a meal.

Part II treats of the Planning and Serving of Meals and adds to this a Practical Method of Calculating Food Values. Consideration is given to the serving of meals without a maid. A chapter on "Dining-Room Courtesy" deals with proper conduct at the dining table. In Part II is also a study of the principles of nutrition and of the selection of foods to meet the requirements of the body.

The appendix contains suggestive outlines for the laboratory work of each part of the book. Several notes to the teacher suggest plans for skillful management of the school kitchen and for modifications of the work to meet the special needs of the pupils.

The entire text has been worked out and tested in one of the largest technical schools in America.

The book is fully illustrated.

Practical Biology

By W. M. SMALLWOOD, of Syracuse University, IDA L. REVELEY, of Wells College, aud GUY A. BAILEY, of the Geneseo State Normal School. 12mo, cloth, 484 pages. Price, $1.25.

PRACTICAL BIOLOGY offers a simple, attractive, flexible, and teachable course in Biology.

Great care has been taken to approach the subject in the simplest possible way. The well-known forms are studied first. The grasshopper, as representative, is studied first among the animals, and the bean seed first among the plants. The practical aspects of Biology are emphasized. A study is made of the economic value of plants and animals, and of the characteristics which make them beneficial or harmful to mankind.

The attractive illustrations are a feature of the Biology. Many of these were taken especially for the book by Mr. Bailey. In addition to the cuts and pictures which illustrate the text, the book contains portraits of the leading biologists of the world, with brief accounts of their lives and of their contributions to the subject.

The flexibility of the book enables the teachers to begin either with the study of animals or with the study of plants.

The book contains a simple introduction defining scientific terms and preparing the way for the regular text matter. The pronunciation and derivation of technical names is given in the text the first time the names occur. Laboratory work is contained in the book, so that a special manual is unnecessary. There are copious drawings and diagrams.

The treatment of human biology emphasizes hygiene and sanitation. Delicate biological questions are tactfully handled. The book contains graphic diagrams illustrating the sections on health and disease. This treatment will be found especially practical. The book has an adequate but sane treatment of alcohol and narcotics.

The book has a number of appendices. One of these has to do with bird study. Another contains the sanitary code of the State of New York.

Each chapter contains summaries, questions, and references.

Elementary Agriculture

By JAMES S. GRIM, of the Keystone State Normal School, Kutztown, Pennsylvania. 12mo, cloth, 518 pages. Price, $1.25.

FARMING is a business — our chief business. But the study of agriculture should be not only economic, it should be educational and social as well. Good homes, good schools, good roads must wait on good business.

In Elementary Agriculture the author utilizes the social values of farm life as educative material; the book aims to make country boys and girls love farm life, not only because this life is worthy and wholesome, but because farming, if directed by a trained mind, is a most interesting and profitable calling.

The social and the economic treatment of agriculture, which have so often been neglected in text-books, take up the first six chapters of Grim's Agriculture; but if teachers prefer, the first lesson may start with corn, and the seasonal sequence of subjects may follow in order. Most teachers prefer to select their own order of chapters to suit local conditions, and to this plan the new book is particularly well adapted.

Elementary Agriculture is written with the idea that the time has come when we must mobilize our instructional resources in agriculture. Dr. Grim recognizes the fact that the study of agriculture is wider than the study of any text-book, and that a book on this subject must be judged by what it leads to as much as by what it contains. The book places emphasis on doing something as a home exercise both for its educational and for its material value; it aims to correlate, when possible, such related subjects as arithmetic, history, literature, geography, and the sciences generally; and it gives pointed suggestions at the end of each chapter for practical and productive work.

The manuscript was carefully read by specialists in the Department of Agriculture at Washington, and by professors in the agricultural colleges of six of the leading states of the country. The book is handsomely illustrated with three hundred and twenty-five pictures.